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REACH CAPABILITY OF MEN AND WOMEN: A THREE-DIMENSIONAL ANALYSIS

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JULY 1978

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AMRL-TR-77-50

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Charles Bates

CHARLES BATES, JR.
Chief
Human Engineering Division
Aerospace Medical Research Laboratory

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This report contains descriptions of the outer and inner boundaries of the 5th, 50th, and 95th percentile grasping-reach envelopes of men and of women. The reach envelopes are intended to guide the placement of critical hand operated controls for the seated operating and working body positions. The most important envelope is the 5th percentile, since it describes that past which 95 percent of the using population can reach. Thus, a controller located at the boundary of this envelope can be reached by an equivalent percentage of the male or

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20. Abstract

female adult populations. A critical review of previous investigations of arm reach and a description of the Aerospace Medical Research Laboratory's Grasping-Reach Measuring Device are presented. The data-gathering procedures and the methods of analyses are included. Applications of the data are also discussed. Data are presented in both graphic and tabular form. Vertical (X-Z) and (Y-Z) planes, and horizontal (X-Y) planes through the various percentile envelopes are presented.

Appendices are included, reporting (1) comparisons between original and final data, (2) reach envelopes for a 50/50 mixed adult male and female using population, and (3) anthropometric data on subject populations.

PREFACE

The work presented in this report was performed under Work Unit No. 71840832, "Design and Evaluation of Work Stations." It appeared originally as a dissertation in Engineering Anthropometry, submitted to the Goodwin Watson Institute for Research and Program Development, Union for Experimenting Colleges and Universities, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The original data were gathered in 1970-71 at the Aerospace Medical Research Laboratory, and were analyzed when the author was admitted to the Goodwin Watson Institute as a candidate for the advanced degree. The dissertation was completed in October 1976. Minor changes have been made in the text to be compatible with altered emphasis and appendices.

The original dissertation includes five appendices. Their titles are as follows: (1) "The Original Reach Data," (2) "Comparative Tabular Data, Original and Final, 5th Percentile, Men and Women," (3) "Technique to Artificially Rotate and Displace Reach Envelopes to Estimate those for Alternate Back Angles," (4) "The Reach Evaluator," and (5) "Anthropometric Data and Descriptions." Appendices I, III, and IV have not been included in this report, Appendix I, "The Original Reach Data," has been deleted so as to conserve space. Appendix III, "Technique to Artificially Rotate and Displace Reach Envelopes to Estimate Those for Alternate Back Angles," has been withdrawn for expansion into a separate technical report. Appendix IV, "The Reach Evaluator," has also been withdrawn for separate treatment. Appendix II, "Comparative Tabular Data, Original and Final, 5th Percentile, Men and Women," has been retained and appears here as Appendix I. Appendix V, "Anthropometric Data and Descriptions," has been retained and appears here as Appendix III.

Appendix II, "Reach Envelopes, 50/50 Men and Women, Tabular Data," is new and is presented here to shed light on changes that occur in reach envelopes that must accommodate to a 50/50 mixture of men and women.

A number of people participated in one fashion or another during the course of this research project. Some contributed directly, and their effects can be easily seen. Others participated in fashions not obvious, but decisive, nevertheless. To them all, I extend my appreciation.

Charles E. Clauser, who took care of a great deal of time-consuming responsibilities on my behalf and critically read the manuscript.

Judy Rolins, Judy Watts, Twila Woolfolk, Lara Green, and Joy O'Hanlon, who recorded and transcribed the rather voluminous mass of data by hand and punched them on data cards.

Edmund and Thomas Churchill and David Nearing, who freely offered statistical advice and/or worked up the formats for the tabular data.

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INTRODUCTION

Accurate reach capability data are essential to enlightened design and layout of driver and crewstation compartments. The days when designers had to make-do with traditional anthropometric measures of arm length have long since passed. Static dimensions, e.g., Functional Reach, Arm-Reach from Wall, and Arm Reach Extended, or fragmented dimensions, e.g., Shoulder-Elbow Distance and Elbow-Grip, are unnecessary as sole sources of information to answer such a question as, "Where should a hand operated control be placed so that a very large percentage of the using population can reach it?" While these, and other, dimensions of the body may be used very productively in other aspects of crew station and workplace design, they are not, of themselves, accurate descriptors of 3-dimensional reach capability. Too many designers, through ignorance, still describe arcs of constant radius from a point designated "shoulder joint" and label their drawing "primary reach zone," or a similar descriptor. There are sufficient data available to avoid such primitive layout techniques. However, there is still a serious lack of comparable reach data on both men and women to guide the placement of critical hand-operated controls.

REVIEW OF THE LITERATURE

When King, Morrow, and Vollmer (1947) reported maximum fingertip reach capability, there were few comparable data in the literature. The Anthropometric Unit of the (then) Aero Medical Laboratory, however, had performed a considerable number of studies on workplace layout, including placement of controls for aircraft cockpits and gun turrets as early as 1942. Although specific data were not available regarding man's reach throughout the range of capability, statistical data on the dimension "Functional Reach" were available. The reach envelope was estimated from the 5th percentile value for this dimension and other anthropometric data gathered on the Army Air Corps and used in the evaluation and layout of work stations. Most of these investigations were documented in reports for distribution primarily within the Army and did not find their way into the open literature. Most of their work, however, was summarized in 1946 in Randal et al. Since then, there have been sporadic efforts in various countries.

King, Morrow, and Vollmer (1947) determined the maximum fingertip reach capability for the right arm at 15°, 45°, 75°, and 105° to the right and left of the midline (0°), from 8 inches below Seat Reference Point (SRP)* to 52 inches above it. The combined reach envelope was presented in the form of horizontal sections at 6-inch levels. The sample consisted of 139 male Navy personnel. The subjects were restrained by a conventional aircraft lap belt and shoulder harness. The investigators calculated the means, standard errors of the means, and standard deviations for maximum fingertip reaches, and from them determined a fingertip reach envelope within which 93 percent of their sample could reach all points on its boundary, and 98 percent could reach any single point on its boundary. It extended from 2 inches below SRP to 46 inches above. Although right arm reach was measured throughout 210°, i.e., 105° to the right and left of the median plane, only that segment extending from the median plane right 75° was considered in the derivation of the reach envelope. The dimensions of this envelope appear in table 1.

*Seat Reference Point (SRP) is the point of the intersection of the midline of the seat with the midline of the seat back.

TABLE 1.

THE MAXIMUM DISTANCE AT VARIOUS POINTS IN THE BOUNDARY AREA FOR OPERATION OF MANUAL CONTROLS.*

ANGLE	0°	R15°	R45°	R75°
Level from Seat Reference Point (Inches)				
46	11.6	13.7	15.0	17.0
40	18.9	20.5	22.4	24.1
34	22.9	24.9	26.6	28.0
28	25.5	27.1	29.1	30.1
22	26.7	28.2	30.3	31.4
16	26.6	28.0	29.7	31.6
10	25.3	27.0	29.3	30.4
4	22.6	24.2	26.4	27.9
−2	17.5	19.7	21.8	22.8

*The maximum distance (inches) at various points in the boundary area for operation of manual controls which can be reached by 97.93 percent of the population at each position and 92.9 percent of the Naval Medical Research Institute (NMRI) series at every position: N = 139 (From King, Morrow, and Vollmer, 1947).

In a later paper, King (1948) reported essentially these same data, but with additional information on the characteristics of the fingertip reach envelope when the subjects were permitted to flex their torsos 18 inches forward. King and Swearingen (1948) used the reach data reported by King, Morrow, and Vollmer to determine the adequacy of placement of controls in the DC-3 and DC-4 aircraft.

Swearingen (1949) described an adjustable cockpit mockup consisting of 15 vertical frames, mounted at 15° intervals to 105° right and left of the median plane. Each frame supported 15 horizontal measuring members. Twenty-one vertical measuring rods were located in the ceiling of the mockup. Altogether, 246 points could be located in space to simulate different sizes and shapes of workspaces. This device appears to have been used primarily in evaluations of existing or experimental workspaces rather than for the derivation of basic reach data.

Sandberg and Lipshultz (1952) studied the maximum reach limits on flat vertical surfaces for application to the layout of radar consoles and communication panels. Fingertip reach capability was determined in frontal planes at distances of 10, 15, and 20 inches from the operators' eyes. Although useful for the purposes intended, such information has only limited application.

Dempsey (1953) described a workspace measuring device with which the maximum, minimum, and "optimum" space requirements of Air Force pilots, when seated in the cockpit situation, could be determined. Intended as a simplification of Swearingen's device, this equipment consisted of a seat and an overhead rack mounted within a vertical plane through SRP. Ten horizontal measuring sticks were mounted at 6-inch intervals on the forward, vertical segment of the rack. Five similar measuring sticks were mounted vertically on the horizontal overhead segment. Each horizontal measuring stick was calibrated to indicate the distance from a knob on its near end to the vertical axis through SRP. The vertical measuring sticks were calibrated to indicate the distance to the horizontal plane through SRP. The seat was mounted on a platform which could be rotated about the vertical axis through SRP. Reach data could be taken at any interval as far as 135° to the right or left of the midline.

Using the workspace measuring device, Dempsey and Emanuel, in 1953, determined the 5th and 95th percentiles for "absolute maximum" reach (equivalent to Dempsey's maximum), "normal maximum" (Dempsey's minimum) and for "optimum" functional reaches. Information was taken only to the right of the midline throughout 135° at 15° intervals, from 6 inches below SRP through 48 inches above it. Grasping reach data were obtained for the shirt-sleeved condition and with the subjects wearing partial pressure suits, first uninflated and, later, inflated. The subjects were securely restrained by a lap belt and shoulder harness in all conditions. The shirt-sleeved results of this study were published in 1963, when they were reported in *Human Engineering Guide to Equipment Design*. The 5th, 50th, and 95th percentile values are given. Unfortunately, however, the drawings accompanying the data incorrectly illustrate handgrip reach instead of thumb-and-forefinger reach.

Dempster (1955) and Dempster, Gabel, and Felts (1959) presented a completely different approach to the description of arm reach capability. Their interest was on specific hand orientations in the "more forwardly-directed positions" (1955, p. 159). Dempster determined the space "in which the hand could range up, down, forward, sidewise, etc., in straight, oblique, or curved paths . . . with the palm and grip angle . . . constantly the same relative to the space of the observer" (ibid., p. 160). Eight orientations of the hand were studied. These were maintained through the use of a special handgrip device and are illustrated in figure 1.

Dempster used the term "kinetosphere" to denote the envelope of the maximum movement possible for a single hand orientation. Each kinetosphere was defined relative to SRP. By combining kinetospheres for hand orientations in a single plane, patterns of motion called "strophospheres" were derived. A strophosphere describes the maximum movement of the hand when permitted three degrees of translatory freedom and one degree of rotatory freedom at the wrist. Dempster developed two such strophospheres for the hand, one including four angles of forearm pronation-supination in transverse (frontal) planes (the

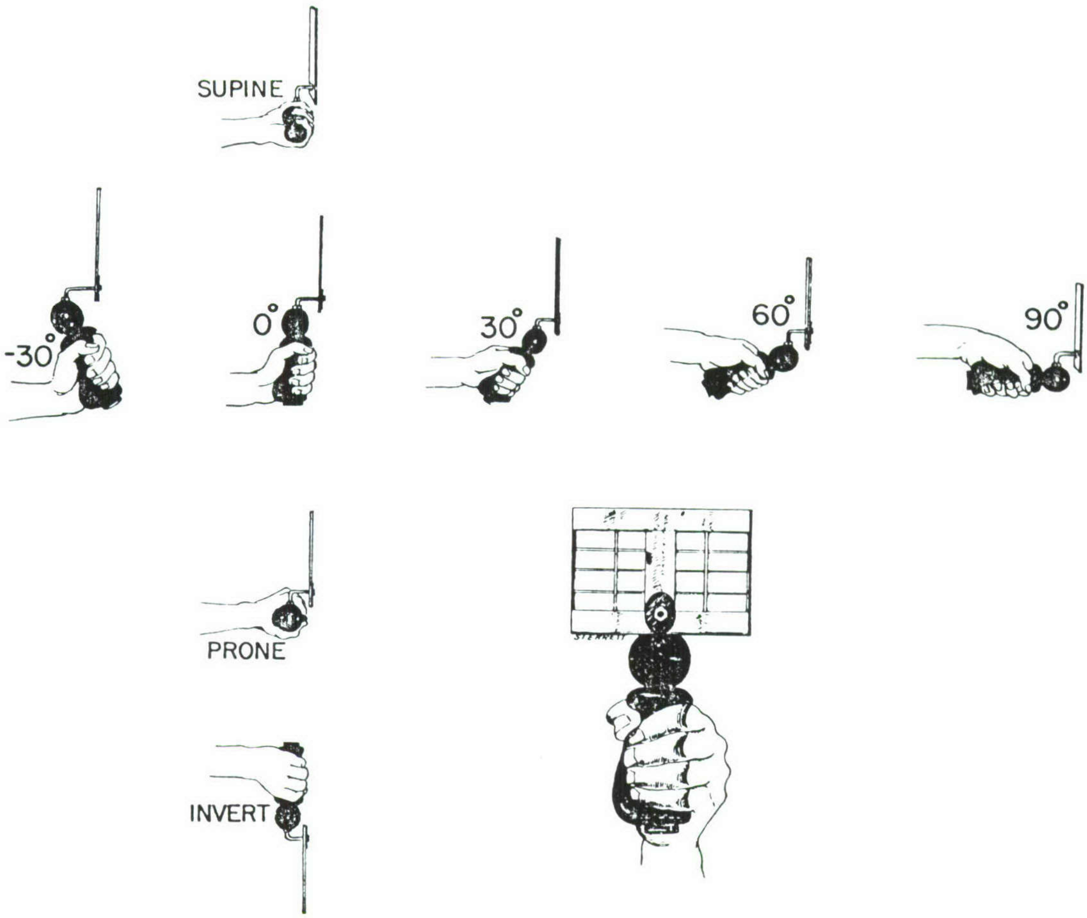

Figure 1. Eight Hand Orientations Used by Dempster and by Dempster, Gabel, and Felts in Their Treatment of Reach Capability.

The handgrip and reference grid used to maintain the hand orientations during recording periods are illustrated. (Modified from Dempster, Gabel, and Felts, 1959, p. 294)

vertical group in figure 1), and another for five angles of radial and ulnar flexion of the wrist in sagittal planes (the horizontal group in figure 1).* The magnitude of translatory motion of the hand was limited only by the restrictions on arm mobility resulting from the necessity to maintain specific handgrip orientations. The mean kinetospheres were illustrated as horizontal, transverse and sagittal sections through their centers of gravity (centroids). Sections through the kinetospheres for each family of hand orientations were then superimposed. See figures 2 and 3. From these data the authors were able to construct a workspace floor plan in the form of horizontal contours at 12-inch intervals, each related to SRP. This is illustrated in figure 4.

These studies of the reach requirements for the seated operator by Dempster and his colleagues were primarily for the purpose of developing "an indirect approach to a functional anthropometry," and secondarily, "to present data which, if intelligently handled, should contribute to the designing of more effective work places, cockpits and driver compartments" (1959, p. 310). Their sample consisted of 22 young university men of muscular to median body configuration.

*Vertical (0°) grip angle is common to both planes; therefore it is represented in both strophospheres.

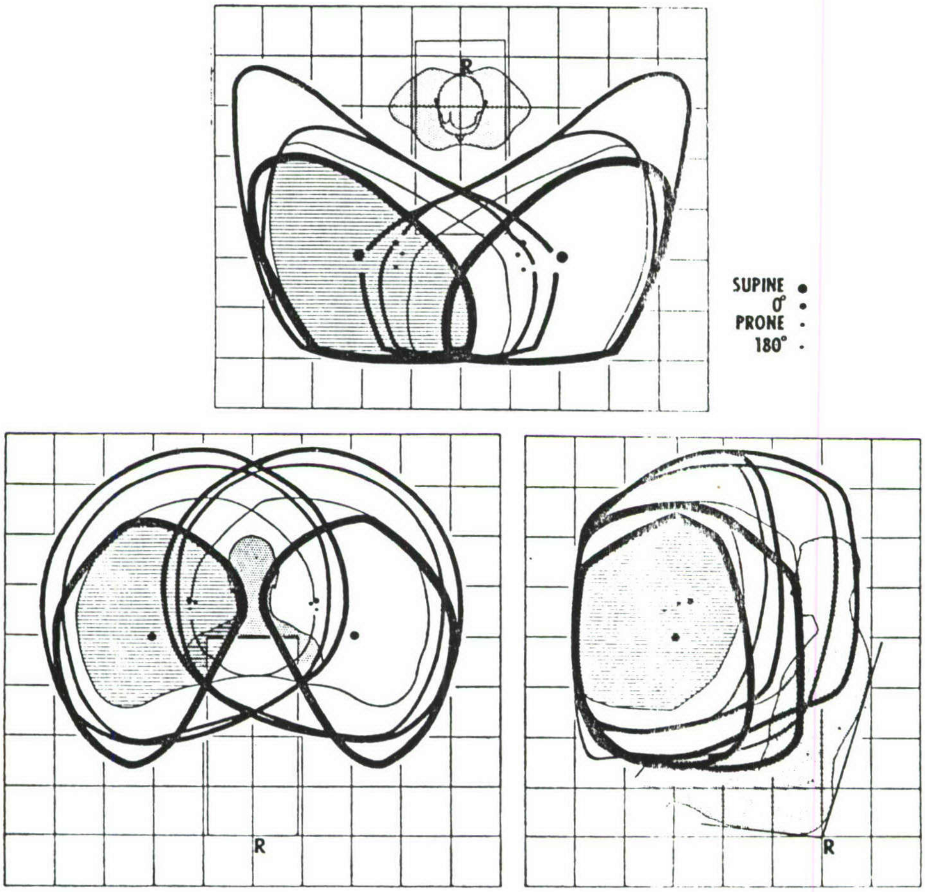

Figure 2. Superimposed Kinetospheres for Grip Orientations in the Transverse Plane. (Shaded areas are those common to all kinetospheres. Dots represent the centroids of the various kinetospheres. [From Dempster, 1955, p. 169, and Dempster, Gabel, and Felts, 1959, p. 309])

In the *Joint Services Human Engineering Guide to Equipment Design,* Ely, Thomson, and Orlansky (1956) described "a vertical, fore-aft cross section through the optimum manual area, bounded by four points (each represented as the center of the operator's fist)" (p. 19). The plane of this cross section passes vertically through the operator's right shoulder. These points are described as follows:

> "*Near Low*: operator's elbows next to body, forearms horizontal."
>
> "*Near High*: operator's elbows next to body, forearms flexed forward about the elbow 15°." (This means 15° above horizontal, to 75°. The forearm swings through 105° from full extension to achieve this orientation.)
>
> "*Far High*: operator's arm extended horizontally from shoulder, operator sitting erect."
>
> "*Far Low*: operator's arms extended and lowered until hand is at level of elbow in Near Low position."

Sections were determined at seven back angles ranging from 0° (vertical) through 60°. See figure 5.

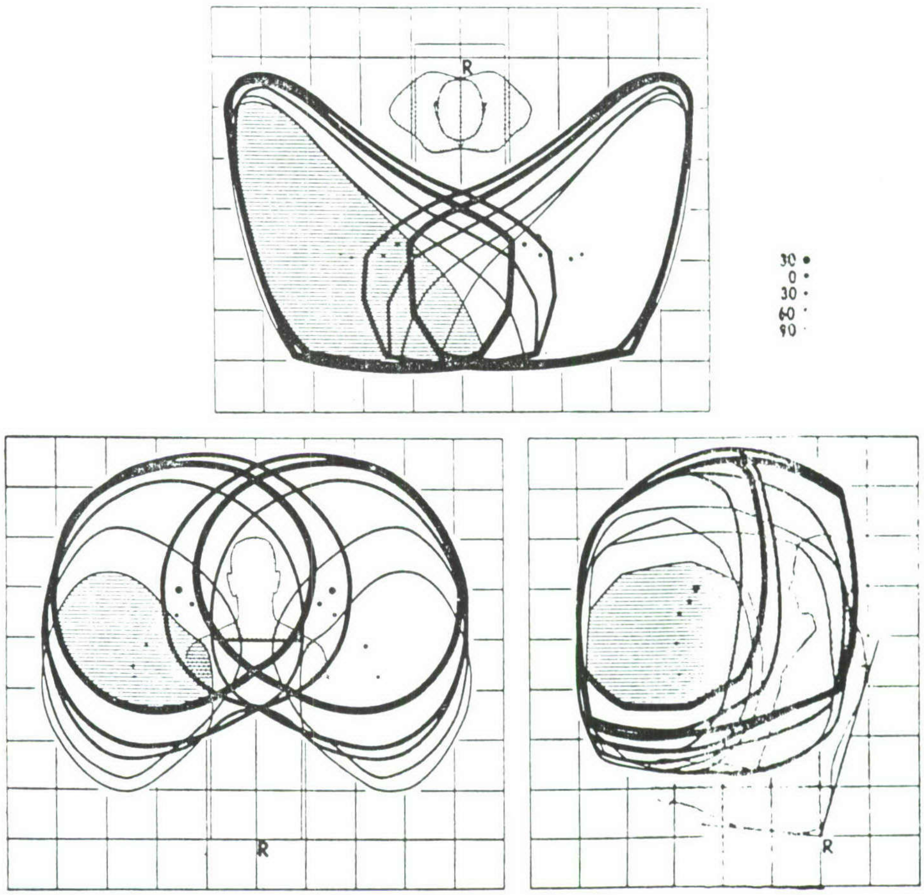

Figure 3. Superimposed Kinetospheres for Grip Orientations in the Sagittal Plane. (Shaded areas are those common to all kinetospheres. Dots represent the centroids of the various kinetospheres. [From Dempster, 1955, p. 168, and Dempster, Gabel, and Felts, 1959, p. 308])

Information that can be extracted from any single section is limited. These are fore-and-aft vertical sections through a segment of the arm reach capability, and are not representative of the total. When the elbow is flexed to form an angle of 90° in the manner described for obtaining the Near Low point, the forearm can be swung laterally throughout an angle of approximately 80° by rotation of the upper arm around its long axis. If the elbow is flexed an additional 15°, to 105°, to attain the Near High point, upper arm mobility is not greatly affected, since its position does not change with respect to the shoulder, where rotation occurs. The upper arm can be swung medially through 10° to 20° with the elbow flexed to 90° or 105°, without materially altering its position with respect to the side of the body.

When the arm is outstretched to reach the Far High and Far Low points, the upper arm is no longer rotated about its long axis to move the forearm through the horizontal plane; rather the outstretched arm is swung horizontally about the shoulder. In such a movement, the upper arm has a much greater range of angular motion. The mean angle for horizontal abduction (movement away from the median plane) of the upper arm is 134°, exceeding lateral rotation of the arm around its long axis by approximately 54°. The mean angle for horizontal adduction (movement toward the median plane) of the upper arm is 48° (ibid.), exceeding medial rotation of the upper arm by approximately 28°. As the hand is moved from the Near points to Far points, rotation of the upper arm around its longitudinal axis becomes less necessary to move the hand through a horizontal arc, and horizontal adduction and

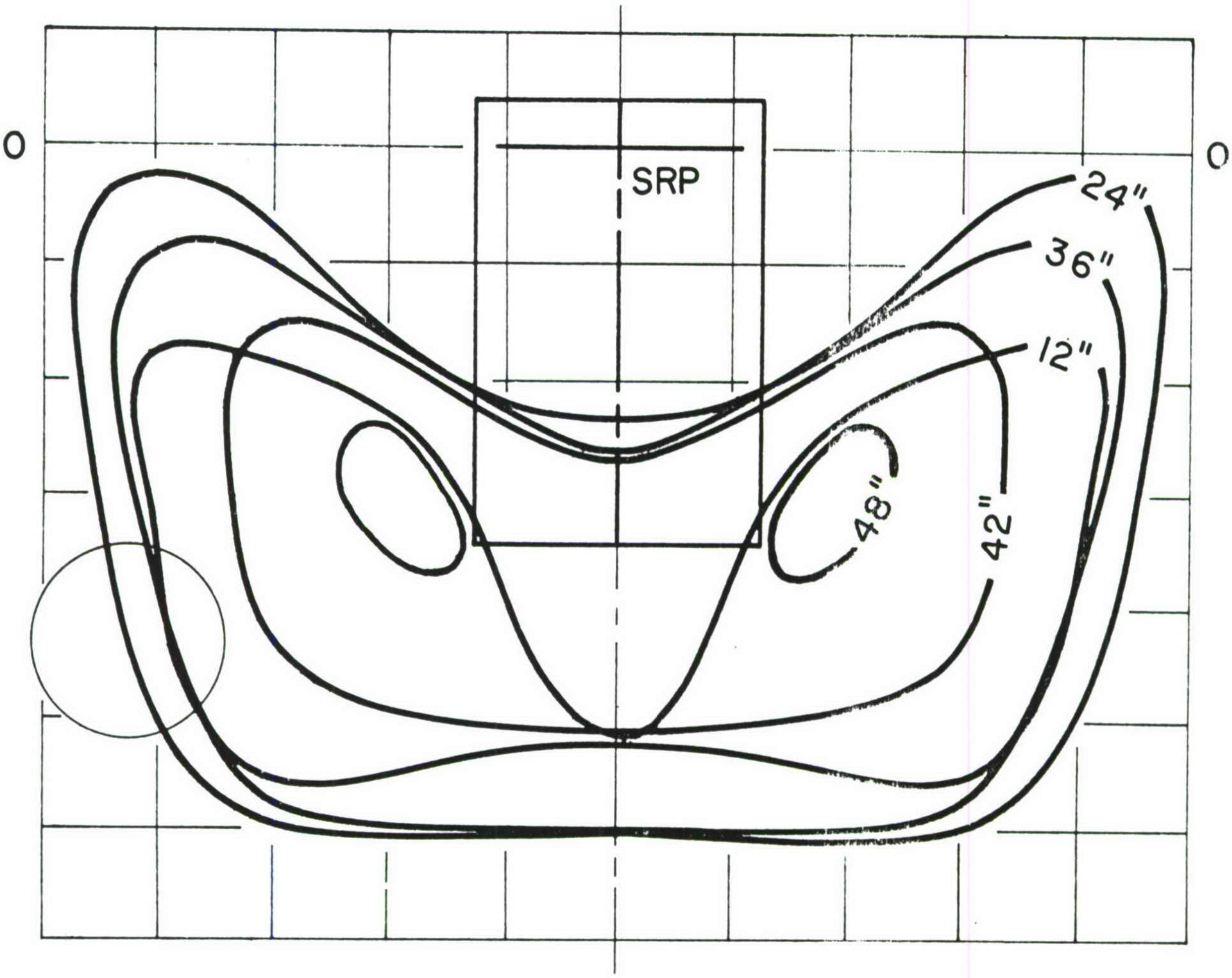

Figure 4. Floor Plan of Workspace Relative to the Standard Seat Shown by 12-inch Contours. (The grid squares are 6 inches. The 12-inch, 24-inch, 36-inch, etc., levels are above SRP level. The radius of the circle represents a width to be added and subtracted from the different curves to include the 5th and 95th percentiles of movement. [Modified from Dempster, 1955, p. 179])

abduction of the arm gradually become necessary. The increased capability to swing the arm horizontally through the Far points produces medial and lateral areas that are not represented by the vertical cross sections in figure 5. Rather, the cross sections are representative of a wedge-shaped central segment of approximately 100°, equal to the range of motion in rotating the arm around its long axis when obtaining the Near points.

Ely, Thomson, and Orlansky (1956) presented maximum fingertip reach curves for the seated and standing positions in the form of scaled charts such as shown in figure 6. Seven back angles between 0° and 60° were treated. Data were presented as capability curves within different planes. The planes considered were at 0° (the median plane) and 12.5°, 38.5°, and 66° to the subject's right.

Some readers may experience difficulty in using the arm reach data as they are presented in figure 6. Although the data represent planes through SRP, they are illustrated, with exception of the 12.5° plane, in the form of foreshortened curves. Information that can be obtained from these charts is limited to the distances from points along the reach curves to the frontal and transverse planes through SRP. The distances from the median plane, however, can only be determined by triangulation. Furthermore, the authors gave no body size information concerning the test sample from which they

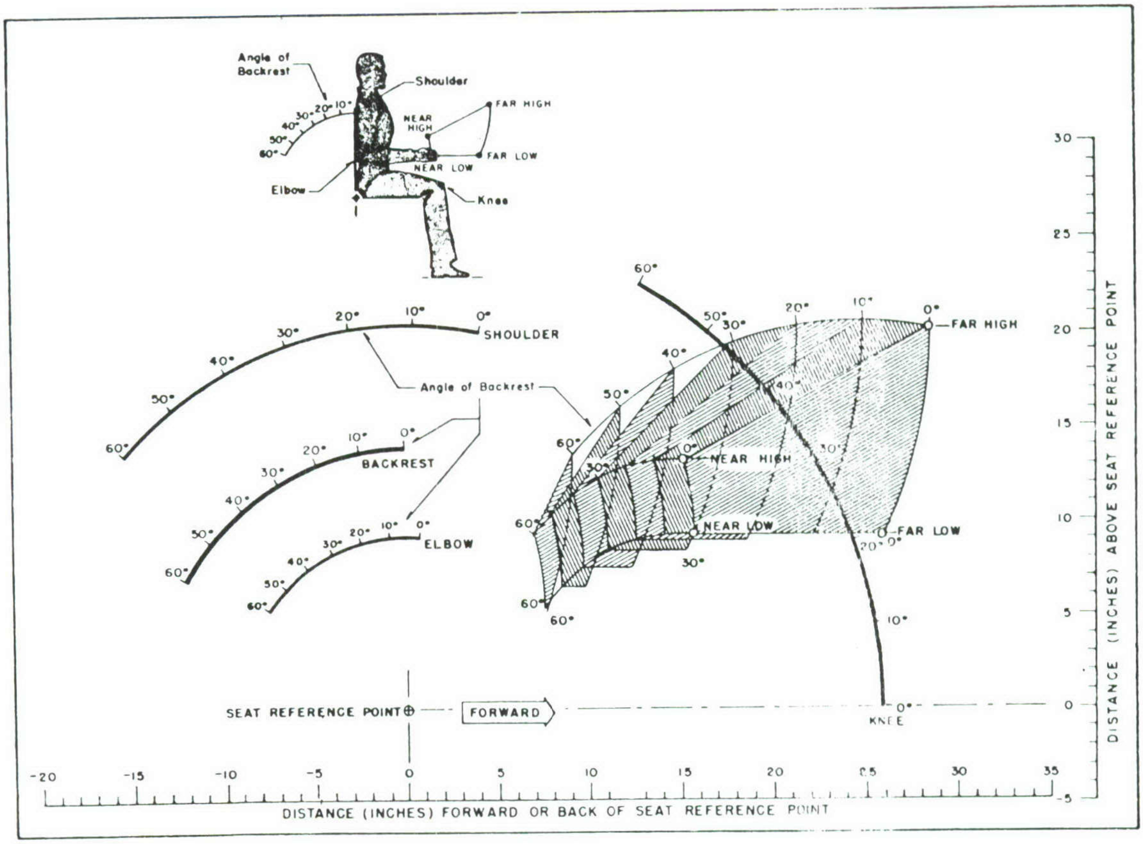

Figure 5. Optimum Manual Areas for Seated Positions. (From Ely, Thomson, and Orlansky, 1956, p. 20)

determined their "optimum area" cross sections and "maximum fingertip" reach curves. Consequently, there is no means by which a designer can judge the appropriateness of the curves for a given population.

The authors refer to the angular positions of the reach curve planes to coincide with the arm angle. With the arm outstretched to the 12.5° position, it is approximately parallel to the 0° (median) plane. (See illustration at the top-right in figure 6.) With the arm in this position, the angle indicated necessarily refers to the reach curve plane. As the arm is swung laterally, the angular difference between the reach curve plane and the axis of the arm becomes less until the reach curve plane runs through the axis of the shoulder. The angle at which this occurs depends upon the relative positions of the SRP and the center of shoulder rotation. In figure 7 they coincide at about 90°. It is only at such a point that the angles of the reach plane and arm will be identical.

Pierce and Murch (1959) treated arm reach (and strength) as influenced by wearing a full pressure suit (Goodrich, Mark IV). Reach information was obtained only on one small subject in the "launch position" (supine), with the suit uninflated, and during the "orbit position" (seated), with the suit inflated to 3.5 psi. All reach data were referred to SRP. With his suit inflated, the subject's arm reach was considerably restricted particularly in the vertical dimension, in which he could reach only to the level of the top of his helmet. Unfortunately, data were not obtained for the shirt-sleeve condition.

P. Frankenstein and Sons (1961) described a measuring device and a method of data presentation by which decrements (or increments) in arm and shoulder mobility may be measured and portrayed. They

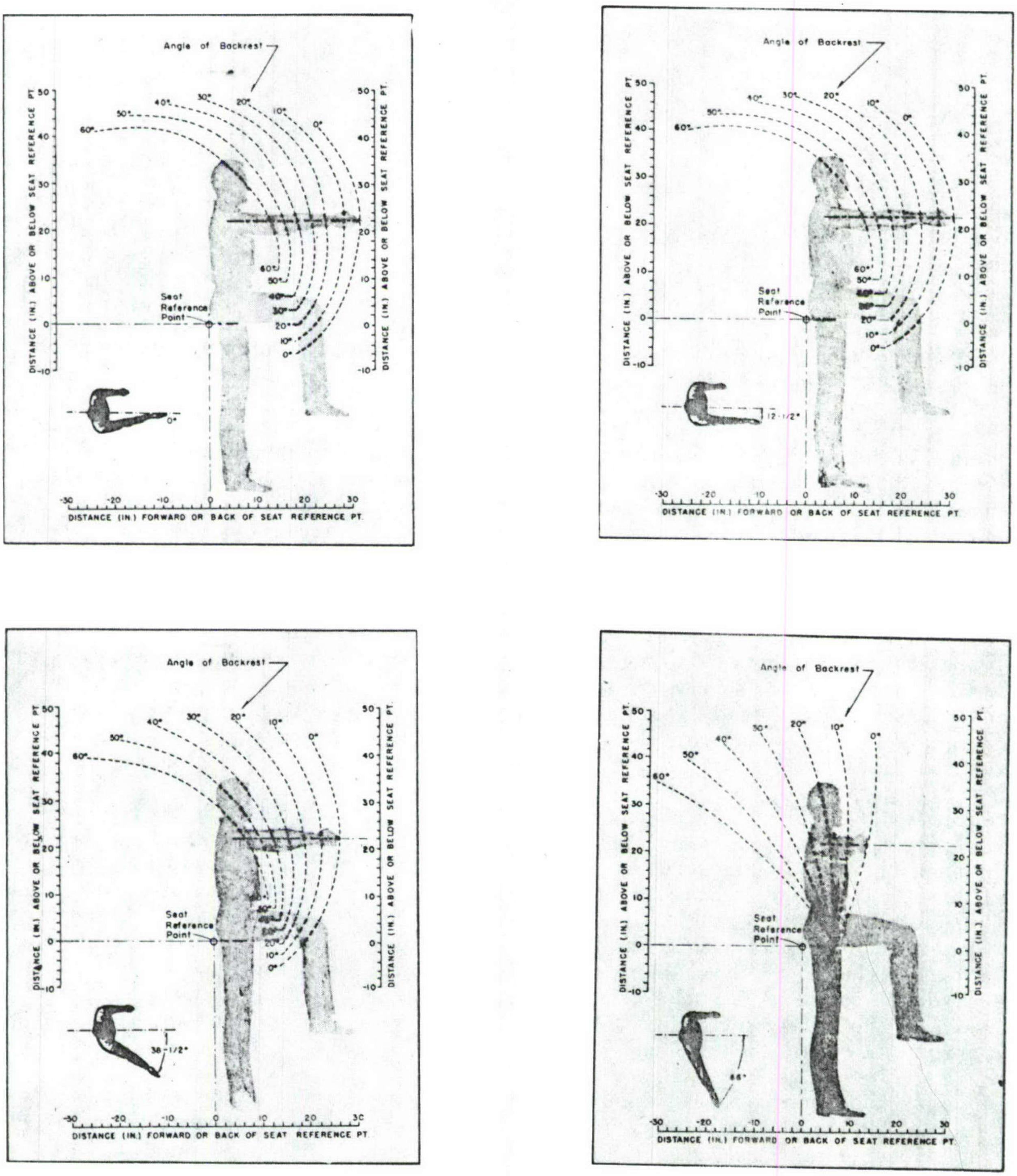

Figure 6. Maximum Fingertip Reaches for the Seated and Standing Positions at 0°, 12.5°, 38.5°, and 66°. (From Ely, Thomson, and Orlansky, 1956, pp. 26, 27, 28, and 29)

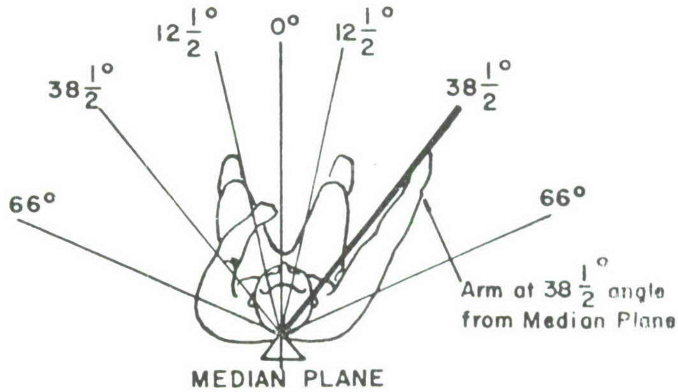

Figure 7. Angles at which Maximum Fingertip Reaches were Measured by Ely, Thomson, and Orlansky, 1956.

designed the device for measuring the mobility of these body parts among patients undergoing orthopedic therapy, and for measuring reach decrement resulting from wearing pressure garments. Wright (1963) also described the device, which consists of a semicircular bar carrying a movable measuring rod. The bar, supported on tripods in front of and behind a chair, is capable of being rotated over the chair. Linear reach measurements are made by touching the end of the measuring rod to the tip of the forefinger. The device is illustrated in figure 8.

Both reports presented data as polar graphs. In these graphs, reach to a point in space is defined by means of the "front angle" (inclination of the semicircular bar), the "side angle" (angular location of the cursor), and the length of the range rod (calibrated to show length of reach from the center of the arch). The angular extremes of reach are defined by plotting front angle against side angle. The distance along these azimuths (recorded relative to front angle) define the limits of reach. The apparatus, then, is used primarily as a mobility measuring device rather than as one to ascertain the complete reach envelope. It is, however, sufficiently versatile to be used for the latter purpose as well.

Kennedy (1964) defined the outer boundaries of the minimum, the 5th, 50th, and 95th percentile grasping-reach envelopes for seated subjects selected to represent the United States Air Force flying population. Twenty adult male subjects were measured using the Aerospace Medical Research Laboratory's grasping-reach measuring device, which incorporated a chair with a back set at 13° aft of vertical and the seat at 6° above horizontal. A diagram of the major features of this device is shown in figures 9 and 10. Reach capability was reported in the form of horizontal contours at 5-inch intervals above and below the SRP level. Within each contour, data were reported at 15° intervals as radii from a vertical through SRP. Examples of the tabular data for the SRP and 30-inch levels are presented as figures 11 and 12. Segments of the data reported by Kennedy (ibid.) and comparable portions of the data from the current study are compared in the Discussion section.

Kennedy (ibid.) reported reach data only for the outside boundaries of percentile reach capability.* As indicated in that report, there is an inner boundary to each envelope that represents the farthest inward that the individual can be expected to reach. This inner boundary is usually along the surface of the body or the body support system, but frequently, such as to the right rear of the subject, just behind the shoulder, the inner boundary is determined by limits to the mobility of joints of the upper limb. These limits of reach are only hinted at in the 1964 Kennedy report.

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*These data also appeared in McCormick (1970), Van Cott and Kinkade (1972), and McConville et al. (1976).

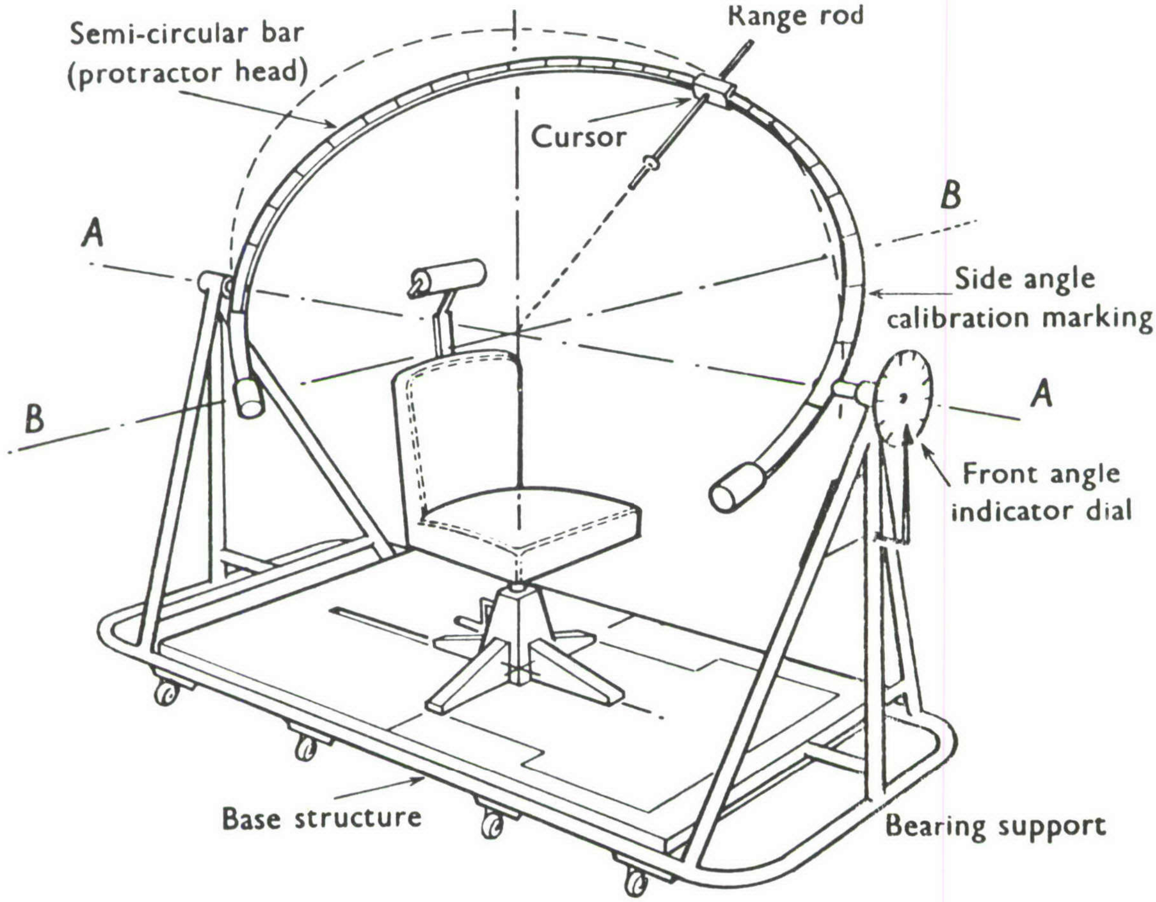


Figure 8. The Frankenstein Anthropometric Measuring Apparatus. (From Wright, 1963, p. 35)

In addition to reach data per se, Kennedy also presented a correlation matrix for anthropometric dimensions and different measures of reach capability. No attempt was made to develop regression equations or to predict the reach capability for other populations. The values for mean reach capability and standard deviations were tabulated for vectors within the angular boundaries of the minimum reach capability envelope.

Chaffee's 1969 report described a method by which reach capability might be measured and presented for application to driving compartment layout. He was concerned with one-handed maximum grasping-reach with the left hand throughout frontal (Y-Z) and left parasagittal (X-Z) planes. The boundary of a driver's reach envelope was called an ergosphere, a more restrictive use than that of Dempster (1955). Ten male and 10 female subjects were used. No anthropometric dimensions are provided. Measurements were taken in a simplified automobile driving compartment without a steering wheel and restraint belts. (Although, as the author states, the belt buckle is used as an important landmark for the location of measuring planes.) Reaches were made to 5 frontal and 5 parasagittal panels to the subjects' front and left. In both arrangements, the panels were equally spaced between the subject's maximum reach forward and to his left, and his belt buckle for the frontal planes, and the left side of the seat for the parasagittal planes. Reaches were made to points on radials generally at 22.5° intervals on each plane. There were 15 such radials on each of the frontal planes and 16 on each of the parasagittal planes. These are found in figures 13 and 14.

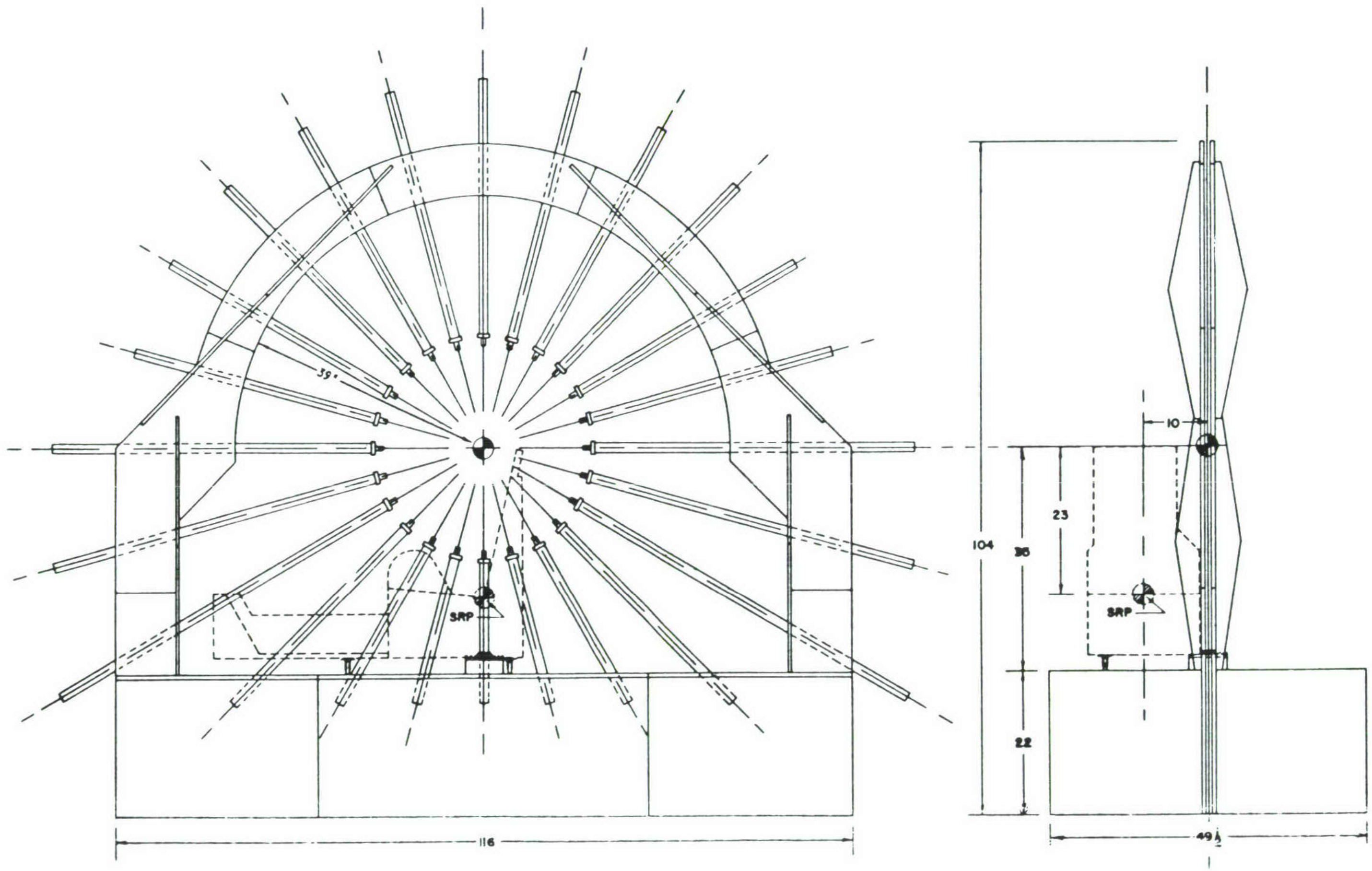


Figure 9. Plan of AMRL Grasping-Reach Measuring Device Platform and Arch
The axis of seat rotation is 10 inches to the right of SRP-V and within the plane of the arch.
(From Kennedy, 1964)

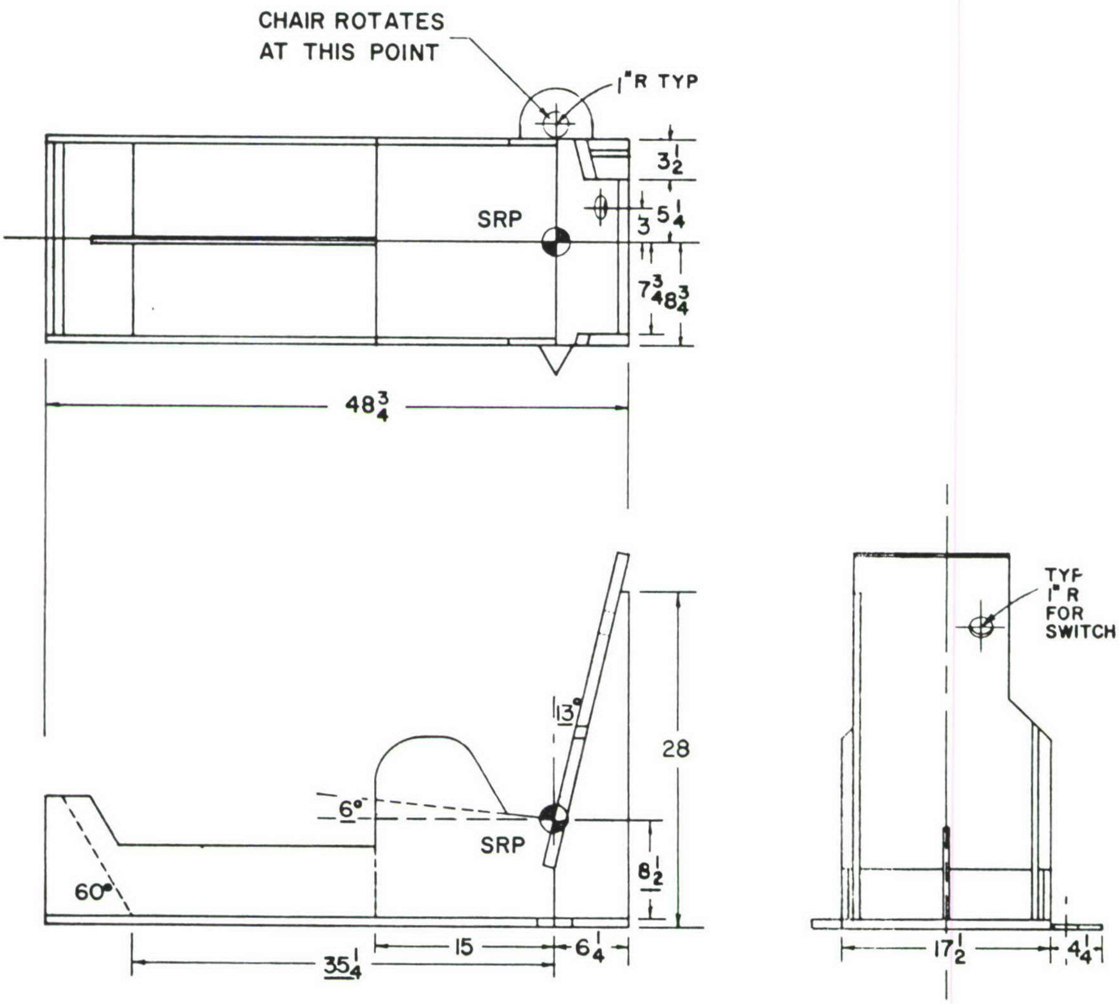


Figure 10. Plan of the Seat for AMRL Grasping-Reach Measuring Device. (Underlined measurements are those that are in accordance with US Air Force design requirements. [From Kennedy, 1964])

Linear Data for Grasping Reach (in inches)

Angle	N	Min	5th	50th	95th
			Percentiles		
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°					
L 75°					
L 60°					
L 45°					
L 30°					
L 15°					
0°					
R 15°					
R 30°	19		17.50	20.75	25.00
R 45°	20	16.25	19.50	21.75	26.00
R 60°	20	17.50	20.50	22.25	26.25
R 75°	20	17.25	20.00	22.25	26.00
R 90°	20	17.00	19.50	22.25	25.50
R105°	20	16.25	18.75	22.00	25.25
R120°	20	15.00	18.25	20.75	24.50
R135°	20	13.00	16.50	19.00	23.50
R150°	19		14.00	16.50	20.25
R165°	13			13.00	17.00
180°					

Seat Reference Point Contours

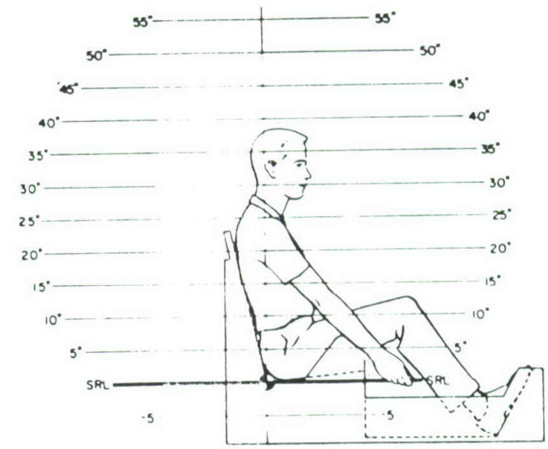


Figure 11. Data Describing the Outer Boundaries of Minimum, 5th, 50th, and 95th Percentile Grasping Reach Envelopes at SRP Level. [From Kennedy, 1964]

Linear Data for Grasping Reach (in inches)

Angle	N	Min	5th	50th	95th
L165°	4				18.75
L150°	4				19.25
L135°	6				20.00
L120°	7				18.75
L105°	9				19.00
L 90°	16			16.75	20.75
L 75°	18			18.75	22.50
L 60°	20	17.00	17.25	20.75	24.50
L 45°	20	18.25	19.00	22.50	26.50
L 30°	20	19.75	21.50	24.50	28.25
L 15°	20	22.00	23.75	26.75	29.50
0°	20	23.75	25.50	28.50	31.00
R 15°	20	26.00	27.25	29.75	33.00
R 30°	20	27.75	29.00	31.50	34.25
R 45°	20	28.75	30.25	32.25	34.75
R 60°	20	30.00	31.00	32.75	35.75
R 75°	20	30.75	31.25	33.00	35.50
R 90°	20	31.00	31.25	33.25	35.75
R105°	20	30.75	31.00	33.00	35.25
R120°	19		30.25	32.50	34.75
R135°	9				34.50
R150°	1				
R165°	2				19.50
180	2				20.25

Percentiles: 5th, 50th, 95th

30-Inch Contours

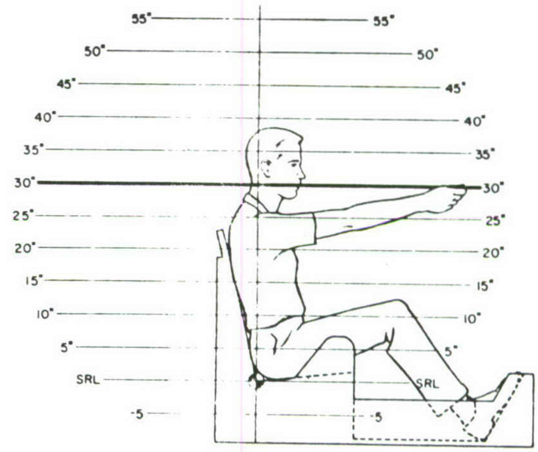


Figure 12. Data Describing the Outer Boundaries of Minimum, 5th, 50th, and 95th Percentile Grasping Reach Envelopes at the 30-inch Level above SRP. [From Kennedy, 1964]

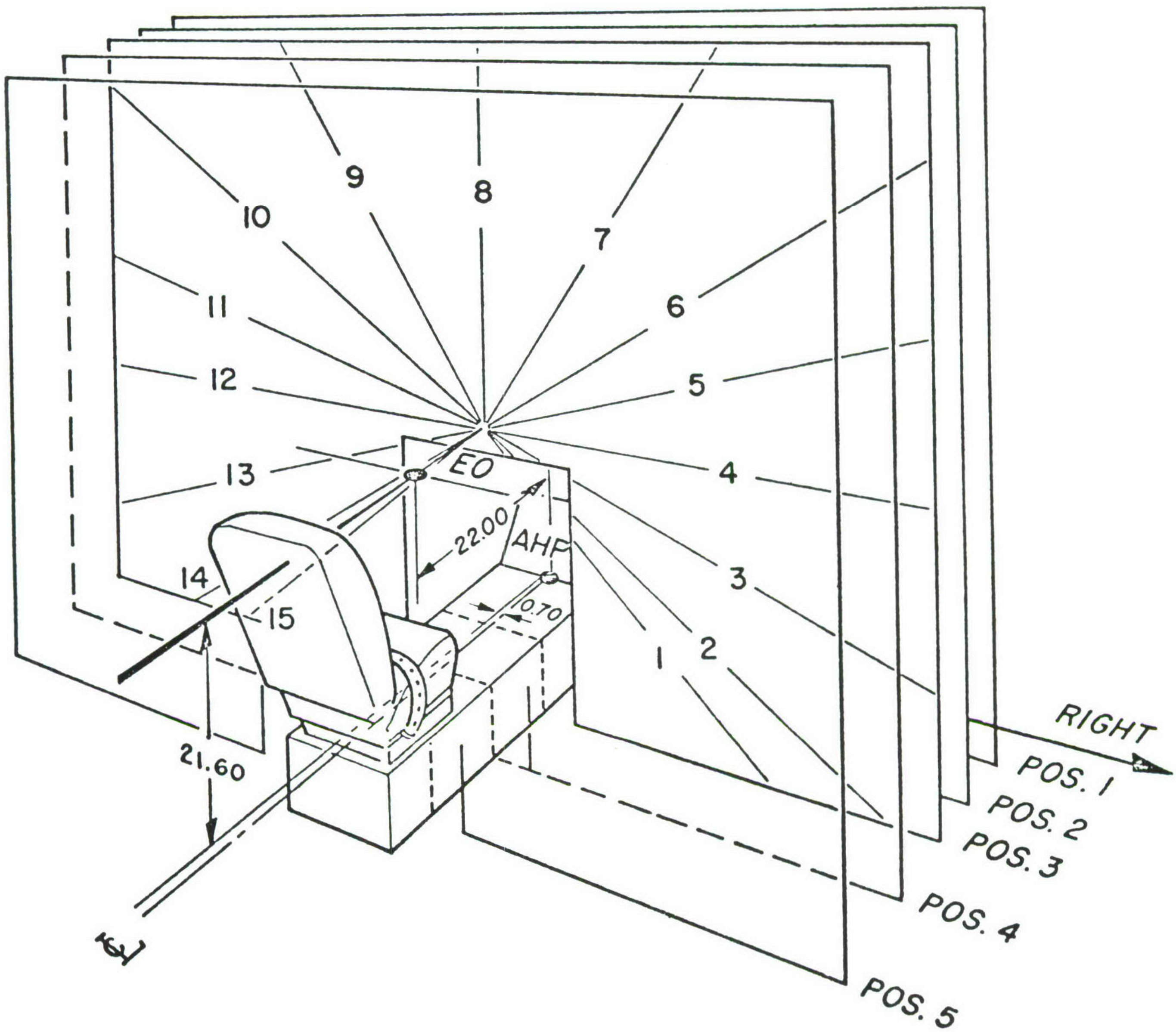


Figure 13. Forward (Y-Z) Reach Panel Positions Showing Radials Along Which Reach Measurements Were Made. [From Chaffee, 1969]

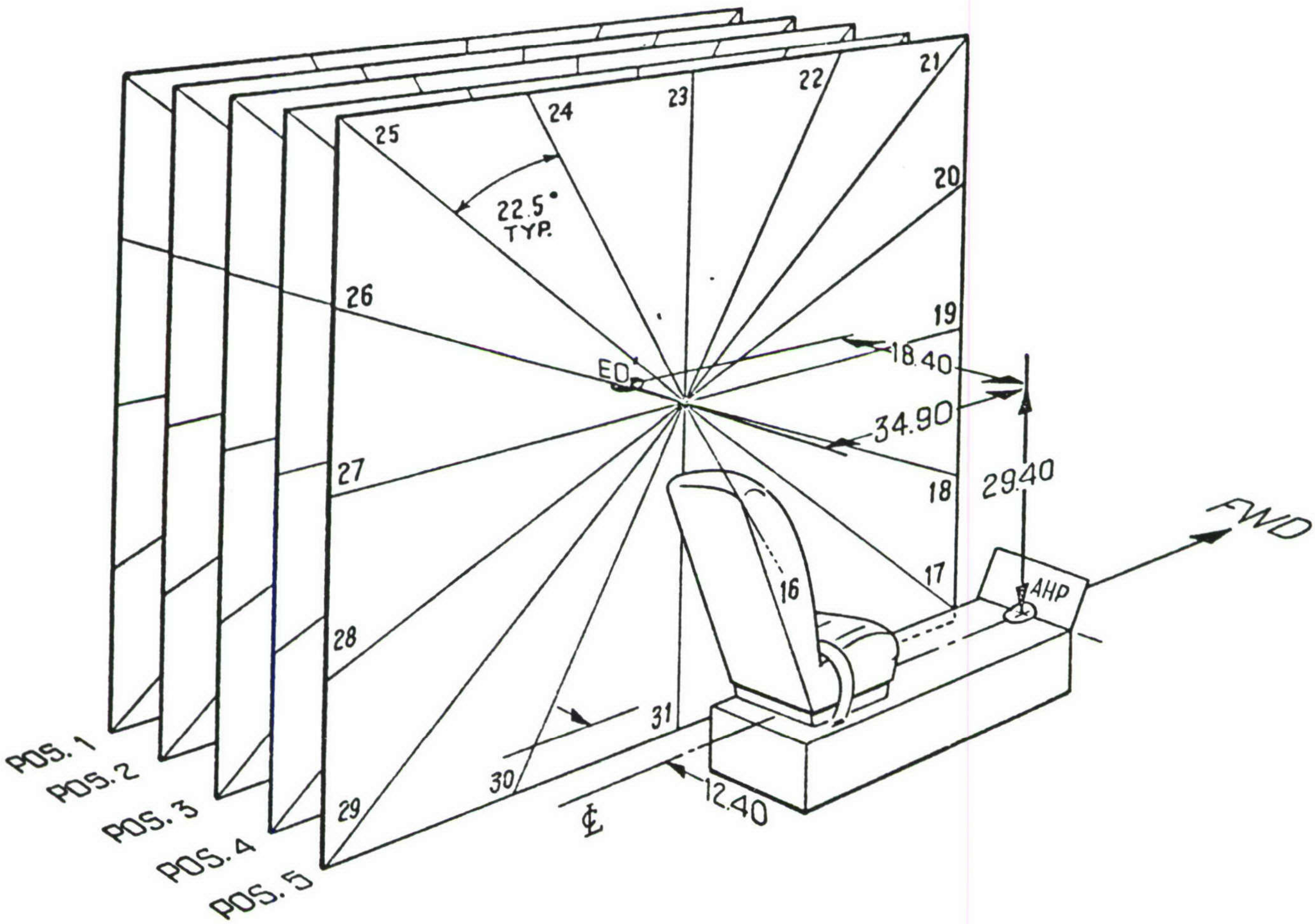


Figure 14. Lateral (X-Z) Reach Panel Positions Showing Radials Along Which Reach Measurements Were Made. [From Chaffee, 1969]

The "best" ergosphere origin (Dempster's "centroid?") was chosen for each radial plane, as constructed from radial reach values in the combined set of frontal (and then parasagittal) planes. The manner in which the ergosphere origin is actually determined is not explained. Chaffee appears to have decided in advance that the distribution of reach values along what he calls a "radial sampling vector" will be normal. This is convenient in that simple statistical techniques can then be applied to determine any percentile value of interest. By his definition, all radial sampling vectors originate at the ergosphere origin. Since the ergospheres are far from spherical, this means that a scatter of such points would need to be averaged to establish the origin for each radial plane. The manner in which a functional ergosphere origin can be obtained for an individual subject's ergosphere is not clear. The driver population ergospheres for 10 men and 10 women were apparently adjusted such that their origins coincided, again, presumably at an average point in space. Figure 15 illustrates a frontal (Y-Z) plane at 22 inches aft of the automotive industry's "accelerator heel point."

Faulkner and Day (1970) reported what they called the "maximum occupationally functional arm reach . . . in front of the operator." The subject population consisted of 137 women. The measuring position was seated at a typical tabletop industrial working surface. Seven measuring rods were mounted parallel and horizontal in a vertical rack mounted on the working surface in front of the subject. The measuring rods were horizontal and parallel and spaced at 1, 6, 11, 16, 21, 26, and 31 inches above the working surface. Reach was performed with a thumb and forefinger grasp.

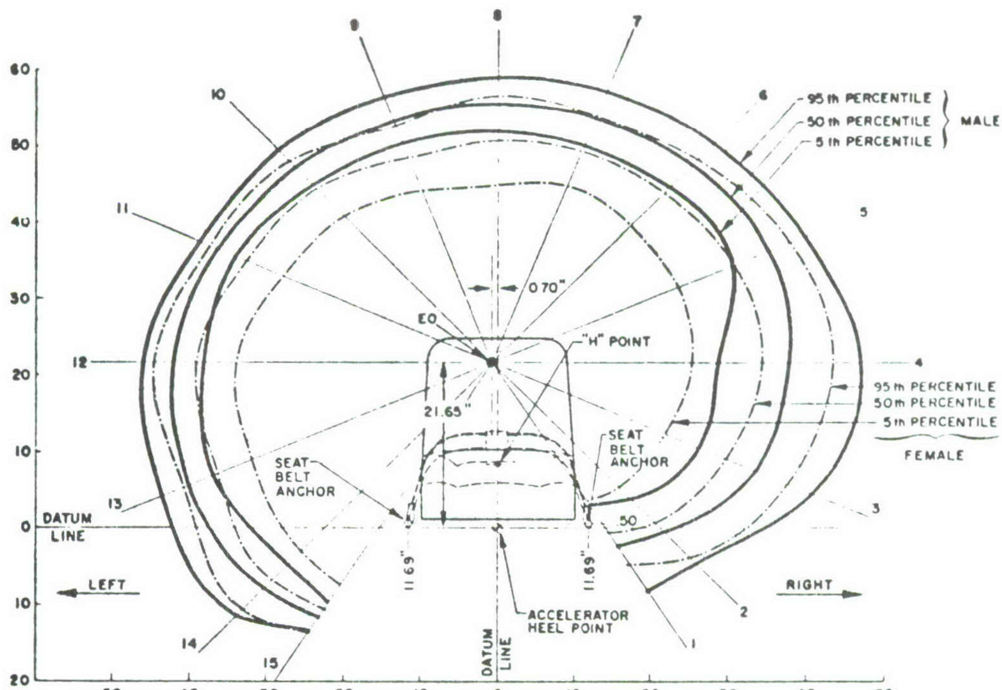


Figure 15. Rear View of Frontal (Y-Z) Planes through Male and Female Reach Envelopes at 22 inches Aft of the Accelerator Heel Point. (Chaffee, 1969)

These planes are all forward of SRP and H point by amounts that varied with each subject, but averaging at about 9 inches.

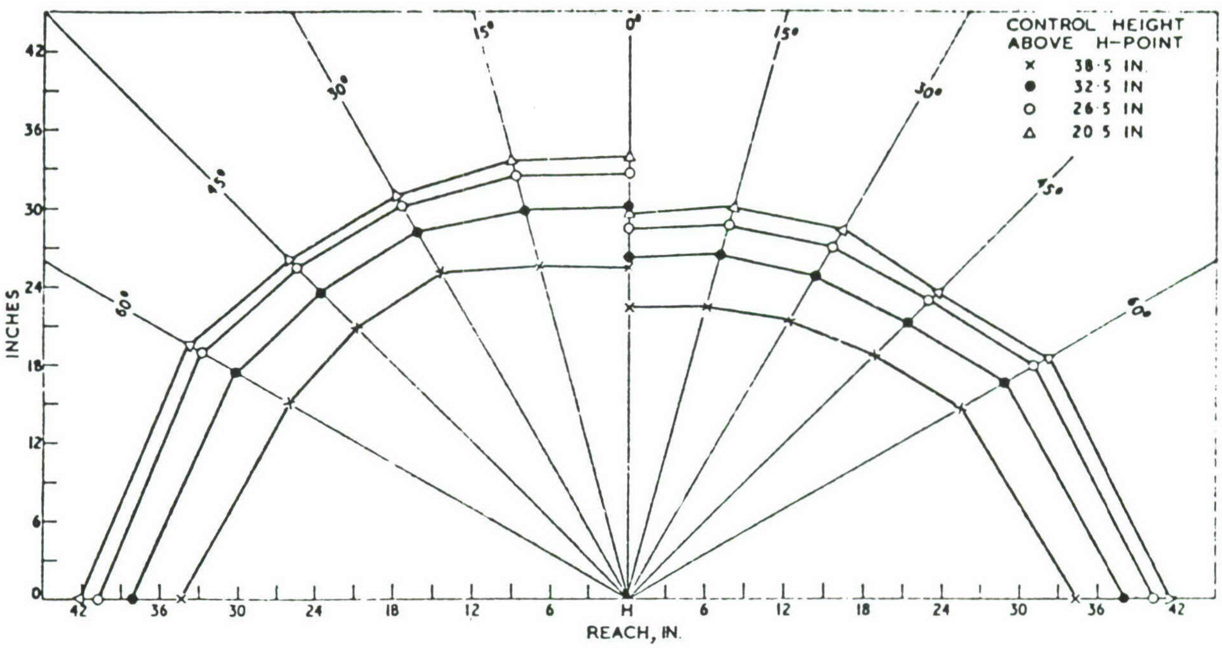
In preparing to gather data, the working surface was adjusted to elbow height, with the near edge, "0" line, in contact with the subject's abdomen. Data were gathered within vertical planes at 15° invervals, apparently from 75° left of straight ahead to 75° right. All data were converted to X-Y-Z coordinates; Z coordinate dictated by the vertical spacing of the measuring rods and Y arbitrarily set at 3-inch intervals. The X coordinate was the dependent variable. Tabular and graphic data are presented to describe the reach capability of "the 5th percentile female operator."

In a report by Haslegrave (1970), we found the establishment of the forward sectors of the 5th percentile female and 95th percentile male reach envelopes. Fingertip reach was of primary concern, although the author stated that grasping reach could be estimated by subtracting 1.5 to 2.5 inches from nearly all radii of the envelopes. The device used was similar to that of Dempsey (1953), Faulkner and Day (1970), and Garrett, Alexander, and Matthews (1970), and consisted of a vertical array of horizontal measuring rods, each of which had a control knob applied to its near end. The measuring rods were parallel and spaced vertically at 6-inch intervals from 3.5 inches below to 38.5 inches above a reference she called "H point." This point was located in the median plane of the seat, 10.5 inches above the floor and 3.75 inches forward from SRP. The distance from SRP to the floor was uncertain.* The seat was lightly padded with a back set at 20° aft of vertical and a seat at 15° above horizontal.

Twenty men and 20 women served as subjects. Fingertip and grasping reach were measured at 0° (straight ahead), 15°, 30°, 45°, 60°, and 90° to the right, with the right hand, and at the same locations in the median plane, and to the left with the left hand. A tightened shoulder sash, apparently over the right shoulder, was used. Data were reported as distances from H point to the measuring levels, projected into the horizontal plane. The "best estimates" for 5th percentile female and 95th percentile male reach envelopes were given. The manner in which the percentile values were determined was not reported. Horizontal contours of the lower and upper halves of the forward sector of the 95th percentile reach envelope were presented for men as were those for the 5th percentile for women. The data were somewhat similar to Bullock and Steinberg's (1973) and Bullock's (1974) in that the reaches for the right and left hands were not symmetrical, except that with the latter data the left shoulder sash restricted reach with the left hand. Haslegrave's (1970) reach with the right hand was obviously restricted when reaching into the forward sector. There were no tabular data. It was necessary to measure from the horizontal contours, either along the planes of reach using the ordinant or abscissa scales or to obtain the Y-Z coordinates of the points within the measuring planes. These contours appear in figures 16 and 17.

Garrett, Alexander, and Matthews (1970) conducted a program to guide the placement of hand controls in aircraft such that they can be reached when wearing selected items of protective clothing. In one experimental condition the subjects wore flight coveralls, flying gloves, a life preserver, and a parachute. In a second, they wore a full-pressure suit, helmet, gloves, life preserver, and a parachute. In the latter condition, data were gathered with the pressure suit inflated to 3.5 psi and again at vent pressure (usually about 0.25 psi). Two data runs were made for each condition, one with an over-the-shoulder inertia reel unlocked, thus allowing the subject to lean forward during his reach, and one condition with the inertia reel locked, securing the subject against the seat-back. Seventeen carefully selected adult male Air Force subjects were used. The grasp-measuring device was similar to the Faulkner-Day device previously described. The measuring rods were oriented horizontally and were parallel. They were mounted in a vertical rack at 6, 12, 18, 24, 36, 48, 54, 60, and 63 inches above the "deck." The battery of measuring rods could be moved to allow reach measures to be taken at 30° intervals, straight ahead and at 30°, 60°, and 90° to the right and left. With straight-ahead reach, the subject always used his preferred hand. Reaches to the right were performed with the right hand; reaches to the left with the left. To obtain crossover reach information, subjects reached to L30° with their right hand and to R30° with their left. A valid reach was obtained when the subject reached with

*This is apparently not the same as the H point used in Stoudt et al. (1970), Stoudt (1973), and described in Society of Automotive Engineers (1970).



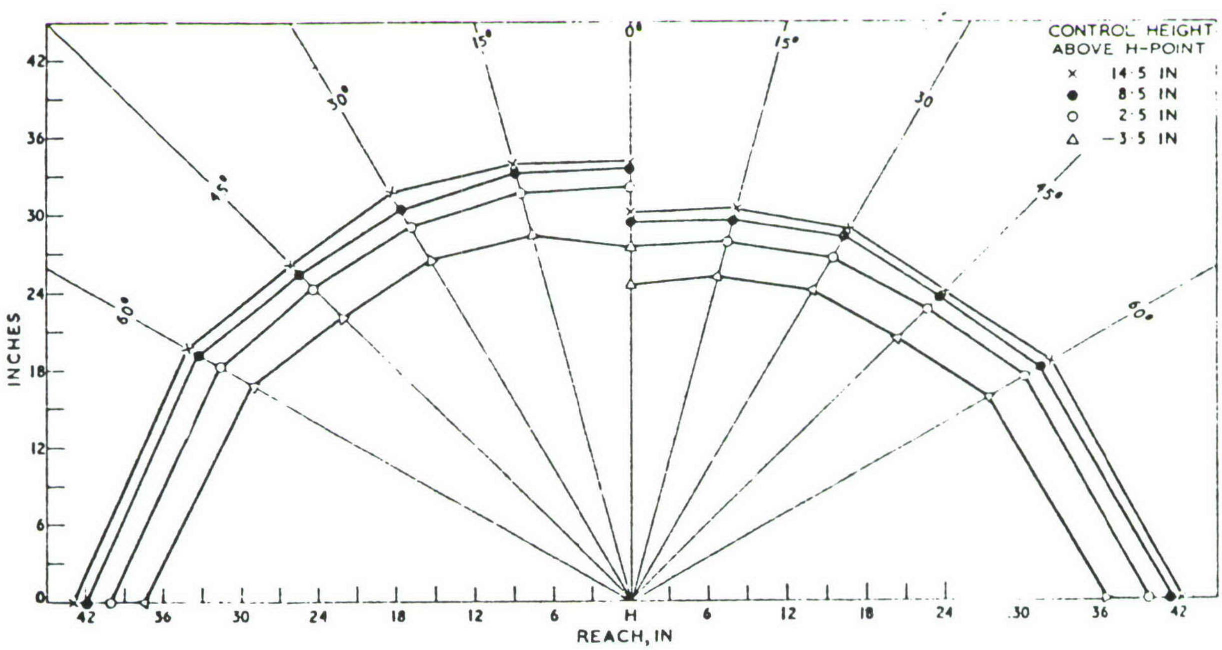


Figure 16. Ninety-fifth Percentile Operating Reach (Men). (From Haslegrave, 1970)

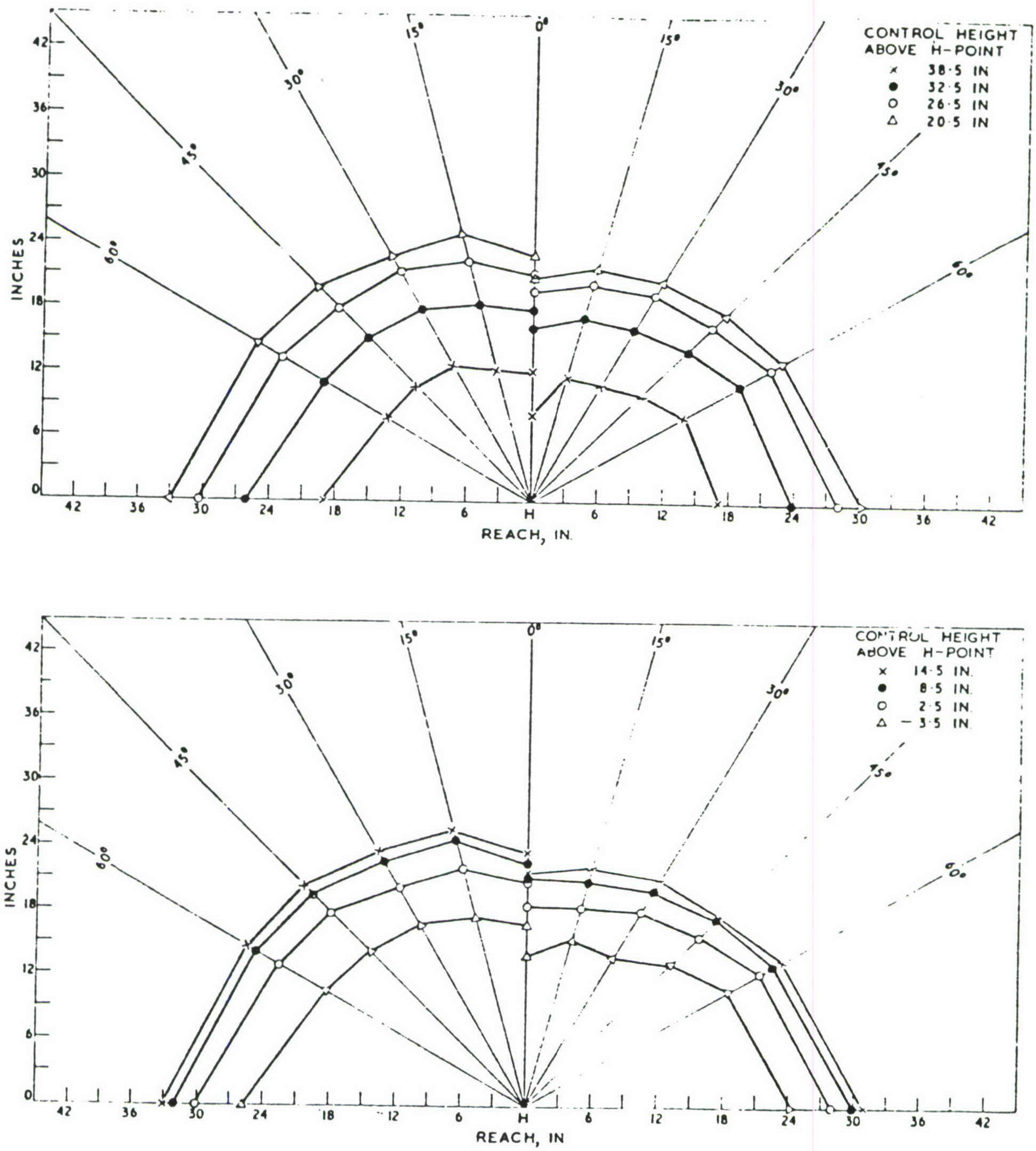


Figure 17. Fifth Percentile Operating Reach (Women). (Haslegrave, 1970)

his thumb and forefinger and retained the capability to turn the knob 90°. All reach data were expressed as horizontal reach distances from a vertical line through SRP along the axes of the measuring rods. Sample data pages are found in figures 18 and 19.

Bullock and Steinberg (1973) and Bullock (1974) studied functional arm reach and presented their findings in an Aviation Medicine Memorandum for the Australian Department of Civil Aviation and in *Ergonomics*, respectively. The latter summarized the effort and will be reported here. The subject population consisted of 75 male and 35 female pilots. Their heights were comparable to those of the Australian pilot population. When measured for reach, they were firmly restrained with a lap and sash (shoulder harness) in an experimental chair geometrically similar to those in private and commercial light aircraft. The measuring apparatus consisted of a vertical rod on which 13 flat buttons 1.5 cm in diameter were affixed. Their placement on the vertical rod was at 13 cm intervals, beginning at 30 cm below SRP and extending to 126 cm above. The vertical rod was suspended from an overhead rail aligned within a plane through SRP. The seat could be rotated such that the plane of the measuring rod could be located at 11 specified angles from SRP, ranging to 110° right and left from straight ahead. Reach measurements were made with both arms; the right arm from 110° right to 15° left; identical, but opposite for the left arm. For their major study, the seat back was set at 18° aft of vertical and the seat at 11° above horizontal.

Reach data were obtained by reaching and making contact with the thumb and the flat buttons mounted on the vertical rack. Data were recorded automatically, using a potentiometer mounted on the overhead horizontal member. A peak detector was used. For realism, all reaches were made with the opposite hand grasping an aircraft control wheel. Subjects were not permitted to slide from beneath the harness.

Reach capability for the right and left hands was assymmetrical, since the shoulder harness did not restrain the right shoulder to the extent that it did the left. The effects of this feature are detectable in their tabular data, where reach capability for the right and left hands is presented to accommodate 95 percent of the Australian civilian pilot population.

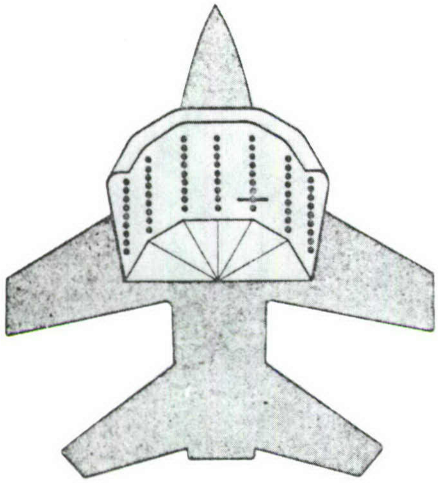
Bullock (1973) also reported changes in reach capability resulting from alterations in seat back angle. Ten subjects were selected at random from each category of body stature. Their reaches were measured again using back angles at 13°, 18°, 23°, and 28°. Seat back and seat "open angle" were held constant at 97°. The authors also investigated the effects of different levels of restraint on reach, including firmly adjusted lap belt and shoulder harness, firm lap belt and 4 inches of slack in the shoulder harness, and firm lap belt and inertia reel "wound out."

Stoudt et al. (1970) and Stoudt (1973) reported their investigations of reach capability and the interrelations between selected traditional static anthropometric measures and functional arm reaches. The aims were to provide useful reach data for automotive use and to predict functional reaches from two anthropometric dimensions. Experimental data were gathered on 50 women and 50 men. Seven anthropometric dimensions were measured. Functional reaches were taken with the right hand to 117 locations to the subject's front and right side. Reach-points were located at 0° (in front of the subject), and at 10°, 20°, 30°, 40°, 50°, 70°, and 90° to their right; and at 4-inch intervals between 1 and 33 inches above H point.* All reaches were reported as distances from H point. The experimental design required a seat back at 25° aft of vertical, a seat set at 17.5° above horizontal, a lap belt which was carefully tightened, and a shoulder strap with 4 inches of slack. Thumb-tip reach was utilized. Photographs were taken, using 35 mm film, apparently such that the film plane was parallel to the reach-point (H point plane). Reach dimensions were read off the photographs.

*Stoudt describes the H point as being 9.0 inches from the floor, 3.8 inches above the seat, and 5.3 inches from the backrest. The H point machine is described in Society of Automotive Engineers Standard J826a, 1970.

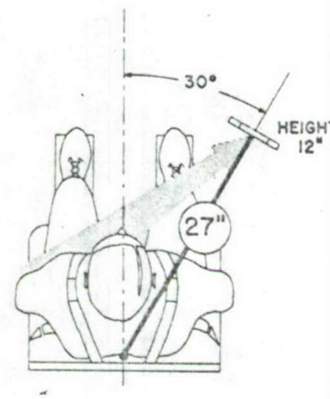
LIGHTWEIGHT FLIGHT COVERALLS

WITH ACCESSORY EQUIPMENT



Seated Eye Height
From Deck—39.50″

Height of Knob Above Deck—12″
Angle From Centerline—R30°



SHOULDER HARNESS UNLOCKED

DESIGN CRITERIA

To manipulate with the **LEFT** hand a rotary knob located 30° to the **RIGHT** of center and 12″ above the deck the knob must be placed no further than 27″ from XSRP.

SUBJECT REACH DATA—SUIT SIZES IN PARENTHESES

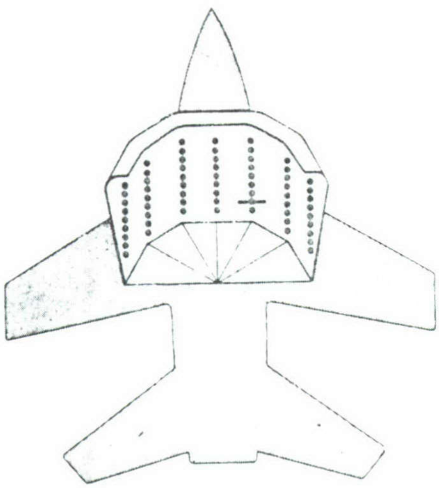
S	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*
1.	39.0	99.1 (SS)	4.	40.0	101.6 (SL)	6.	38.0	96.5 (MR)	8.	38.5	97.8 (ML)
2.	37.5	95.3 (SR)	5.	36.0	91.4 (SL)	7.	32.0	81.3 (MS)	9.	40.0	101.6 (ML)
3.	37.5	95.3 (SR)									

S	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*
10.	39.0	99.1 (LR)	12.	37.5	95.3 (LL)	14.	33.5	85.1 (XLR)	16.	35.5	90.2 (XLL)
11.	27.0	68.6 (ML)	13.	38.5	97.8 (LL)	15.	39.0	99.1 (LR)	17.	34.0	86.4 (XLL)

Figure 18. Reach Capability at R30°, 12 Inches Above the Deck, Lightweight Flight Coveralls, Shoulder Harness Unlocked. [Garrett, Alexander, and Matthews, 1970]

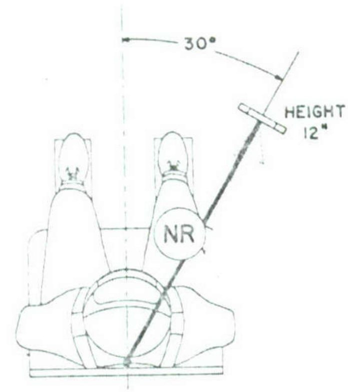
FULL PRESSURE SUIT
INFLATED

WITH ACCESSORY EQUIPMENT



Seated Eye Height
From Deck—39.50″

Height of Knob Above Deck—12″
Angle From Centerline—R30°



SHOULDER HARNESS LOCKED

DESIGN CRITERIA

To manipulate ... ed 30° to the
RIGHT ... ob must be placed no
f...

NOT RECOMMENDED

SUBJECT REACH DATA

SUIT SIZE	SMALL REGULAR			SMALL LONG			MEDIUM REGULAR			MEDIUM LONG		
	S	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*
	1.	23.0	58.4	4.	26.5	67.3	6.	—	—	8.	25.0	63.5
	2.	25.0	63.5	5.	22.5	57.2	7.	—	—	9.	23.5	59.7
	3.	22.0	55.9									

SUIT SIZE	LARGE REGULAR			LARGE LONG			X-LARGE REGULAR			X-LARGE LONG		
	S	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*	*S*	*in.*	*cm*
	10.	—	—	12.	25.5	64.8	14.	—	—	16.	26.0	66.0
	11.	25.0	63.5	13.	25.0	63.5	15.	26.0	66.0	17.	24.0	61.0

Figure 19. Reach Capability at R30°, 12 Inches Above the Deck, Full Pressure Suit, Inflated, Shoulder Harness Locked. [Garrett, Alexander, and Matthews, 1970]

Correlation coefficients were calculated for reach distances, 7 anthropometric dimensions, and age, weight, and Heel-point to H point distance. Stoudt (1973) presented correlations between these 10 dimensions and reaches at 0°, 10°, 20°, 30°, 40°, and 50° and levels at 5, 9, 13, and 17 inches above H point. He provided prediction formulae (regression equations) for estimating reaches from the anthropometric dimensions elbow-fingertip length and shoulder-elbow length. Standard deviations (standard errors) of the estimate were included. He was careful to point out that these estimates apply only to the seated and reach conditions set forth in his experimental design.

Laubach and Alexander (1975) studied the decrement imposed on reach capability from wearing the complete USAF winter flying assembly. Baseline data were gathered with the subject in shirt sleeves, restrained with a lap belt and shoulder harness, and with the inertia reel (attached to the shoulder harness) unlocked. Reach capability gathered under these conditions was compared with that possible when wearing the winter flying assembly, but with the inertia reel locked. Thirty-two USAF pilots served as subjects. Reaches were measured at the same locations as by Garrett, Alexander, and Matthews (1970), but with the measuring device described by Alexander, Garrett, and Riepenhoff (1973). The authors found drastic reductions in reach capability resulting from wearing the winter flying garments with the locked inertia reel, especially overhead, across the body and to the right and left rear. Unfortunately, their procedure did not permit separating out the contributions of each decremental factor. No attempt was made to interpolate reach values between measuring planes.

While there have been a number of efforts to describe reach capability, most have been limited to one or a few sectors of the total reach capability envelope, usually the front and part of the right or left sides. In only one study, Kennedy (1964), there was an attempt to describe the complete range of one aspect of reach capability. In this study he described the entire outer boundaries of the minimum, the 5th, 50th, and the 95th percentile reach envelopes for adult males.

Until the appearance of Chaffee's 1969 effort, there were essentially no data available on the reach capability of women. Chaffee's (ibid.) data were limited to three-fingered grasping reach in the front and left sectors from maximum reach to the subject's abdomen and the left side of the chair, respectively. Ten men and 10 women served as subjects and were analyzed separately.

There are questions regarding Chaffee's (ibid.) technique in selecting what he calls the "Ergosphere Origin," which is, in effect, an instantaneous center of a segment of the reach arc. The radii, or as he called it, the "Radial Sampling Vector," should ideally be perpendicular to the tangent of the reach arc. For the ergosphere origin of one segment of the reach arc to be coexistent with that of another segment, or with the entire ergosphere, the reach envelopes must be spherical. This is not the case.

Chaffee (ibid.) takes the *a priori* position that the distribution of reach values along a given radial sampling vector will be Gaussian (normal); that it will take on what is called a "bell-shaped" distribution. While Haslegrave (1970) did not measure or report reach as distances from an equivalent point, she stated that her data were not distributed normally, but skewed to the right. After examining her reach boundaries and those of several others, it is difficult to accept Chaffee's (ibid.) premise of normal distribution except for small segments of the envelopes.

Bullock and Steinberg (1973) and Bullock (1974) have presented very useful data on both male and female pilots for reaches into the right-front quadrant for the right hand and in the left-front for the left. The experimental situation was purposely designed to yield data applicable to aircraft cockpits.

Stoudt's (1973) study of the interrelations between anthropometric dimensions and reach distances included 50 men and 50 women. The seat structure was typical of automobiles. Reach was limited to the right-front and reported as distances from H point.

No investigator has yet attempted to describe the entire reach envelope for the seated position. Although Kennedy (1964) did report the complete outer boundaries of minimum, 5th, 50th, and 95th percentile envelopes, he readily acknowledged the importance of deriving the inner boundaries. His study considered men only; equivalent data on women do not exist.

Bullock's (1973) survey of Australian male and female pilots of light aircraft revealed that the situation with regard to the positioning of hand operated, critical controls is not yet as good as it should be. The purpose of the survey was to gather information regarding the accessibility of hand operated controls as well as on general body accommodation in aircraft. It was found that pilots still experience reaching difficulties. The author's analysis of her data indicated that "some modifications to the aircraft or to its installations need to be made to ensure the provision of safe restraint for pilots while allowing them to reach all controls" (ibid., Abstract).

THREE-DIMENSIONAL ANALYSIS
PURPOSE

The purposes of the study reported here are to derive the complete, 3-dimensional, 5th, 50th, and 95th percentile grasping-reach envelopes of men and of women, for the seated operating position; and to describe these envelopes in such a fashion as to be readily usable by designers and engineers to locate positions for critical hand-operated controls in machine and vehicle operating compartments.

APPARATUS

To derive information on reach capability, the Aerospace Medical Research Laboratory Reach and Strength Measuring Device was used. It includes a rotatable hard seat mounted on a platform beneath an arch so that the Seat Reference Point (SRP) of the seat lies in the plane of the arch. See figure 20. One side of the arch contains frictionheld measuring rods radiating at 15° intervals, so that each points to the center of the arch. Each rod is calibrated to indicate the distance from the center of the arch to the mid-point of the knob at the inside ends of the rods. The other side of the arch is equipped with hand and arm strength measuring equipment.* The seat's axis of rotation runs vertically through its SRP and the center of the arch. The SRP is 24 inches (61 cm) below the center of the arch. Thus, the center of the arch is at the level of the shoulders and remains fixed with respect to the subject as the seat is rotated. The vertical line through SRP and the center of the arch are referred to as Seat Reference Point-Vertical (SRP-V). This design permits the subjects to push the scaled rods along lines radiating from shoulder level, regardless of the orientation of the seat. Consequently, one measuring rod was not significantly more or less difficult to push or pull by virtue of its orientation with regard to the shoulder joint.

Casters attached to the bottom of the seat facilitate its rotation. The casters are located to clear the ends of the rods when the chair is rotated on the platform. A circular band of sheet steel fastened to the surface of the platform provides a track on which the seat casters roll. Without such a track, the casters would quickly wear a rut in the surface of the platform. A circular scale marked at 15° intervals is painted on the platform around the pivot of the seat. A pointer in the foot support area of the seat indicates the angular orientation of the seat with respect to the measuring plane.

Two large button switches, lightly spring-loaded, were installed in the back of the seat, 18 inches above SRP and 3 inches to the right and left of the seat-back centerline. When the subject is seated, the

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*The basic features of this device were developed by the author. Engineering drawings were prepared by the Design and Drafting Branch, Aerospace Medical Research Laboratory. The device was fabricated in the shops at Wright Field, Dayton, Ohio. Strength data gathered using this apparatus appeared in Thordsen, Kroemer, and Laubach (1972).

Figure 20. The Aerospace Medical Research Laboratory's Reach-Strength Measuring Device

weight of his back against the switches energizes two lights at his feet; on the right and left sides and operates by their corresponding switches. Should a light ever go off during reach measurements, the subjects know they are out of position and must repeat the measurement. The right light is the most important, since all reaches are made with the right hand. The lights function as a warning, primarily during establishment of the forward and left sectors of the reach envelope, when loss of contact between the subject's back and the seat back is most likely to occur. The measuring chair is shown in figure 21. The back switches are attached within the two holes in the seat back, and adjusted so that they are activated when the surface of the switch coincided with that of the seat-back.

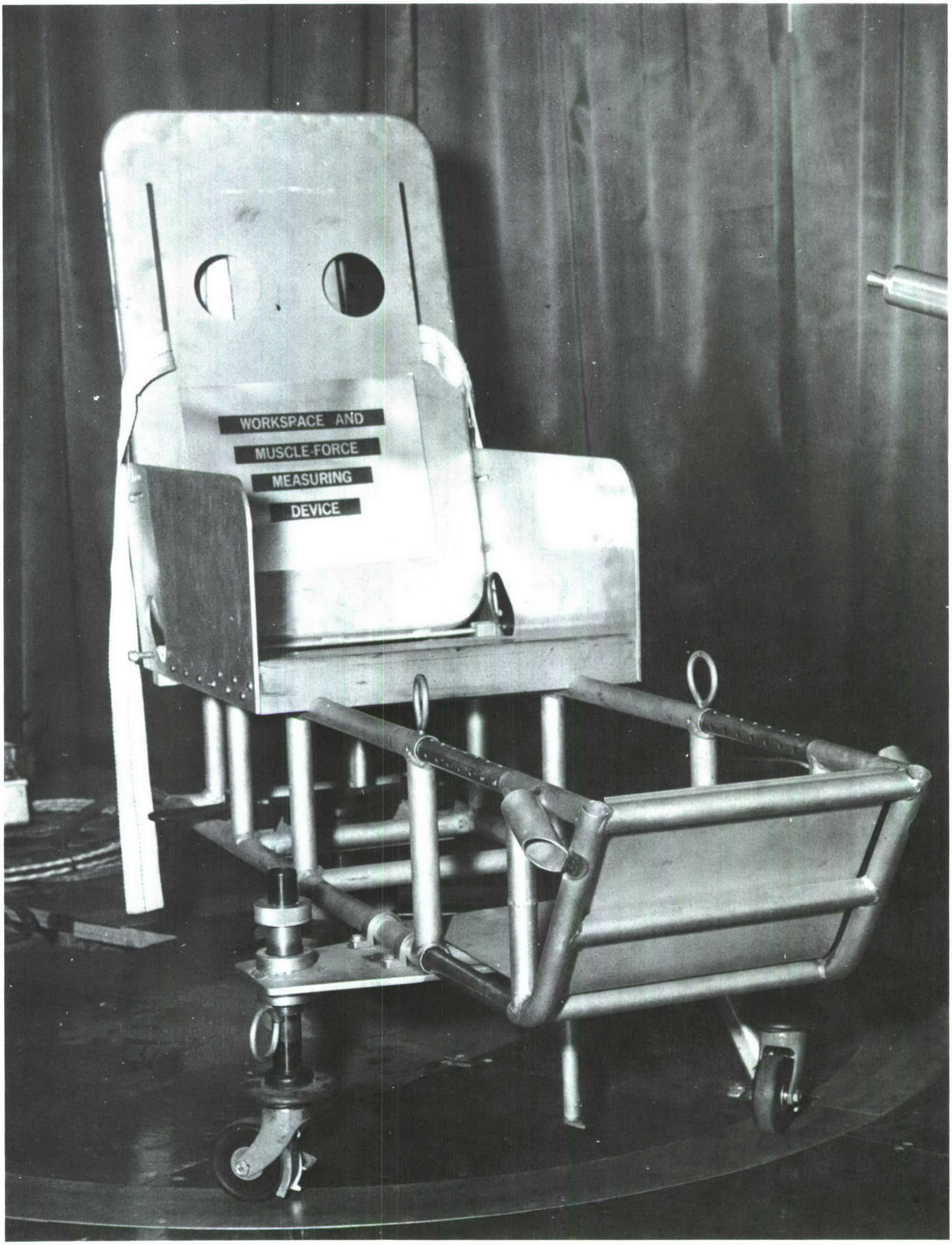

Figure 21. The Reach-Strength Measuring Chair

PROCEDURE

Before each measuring session, the subject* was given time to read an instruction sheet explaining the purpose of the study, the workspaces in which the data would most likely be used, the mechanics of operation, and the approximate length of time to complete the run. After reading the instructions, the subject was encouraged to ask questions regarding any procedure about which he was unsure, such as how to grasp the knobs on the measuring rods with his thumb and forefinger, how to center himself in the seat, and "how far" to push the measuring rods. The thumb and forefinger grasp is illustrated in figure 22. If the subject did not ask questions concerning the procedure, the operator made certain they were clear by discussing them. The essential points were as follows: After sitting in the seat, the subject was requested to look down toward the foot rest area and, with the full length of his back firmly against the seat back, to center his torso on the seat. At this point, his position was examined by the operator and, if necessary, corrections were made. The subject was asked to "memorize" this position and to check it before each reach. The investigator observed the subject's body position frequently during the measuring session. The subject was reminded that this was not a contest, that the measuring rod should first be pulled toward the body with his right hand as far as possible and, after data were transcribed, to push it away only until the arm was fully extended, all without pulling either shoulder away from the seat back. If in manipulating a measuring rod, the subject released one of the back switches, that particular reach was retaken. Each subject was cautioned to take his time, to prevent unnecessary fatigue. The subject was then allowed to manipulate the measuring rods and to practice orienting himself in the seat. Each run lasted approximately one hour.

Reach throughout the forward half of the mid-sagittal plane (0°) was always the first to be measured. Because of the interference of the footrest, the measuring rods at −45°, −60°, and −75° could not be used. The seat was then rotated to the left (counter-clockwise) and reach measurements were taken at 15° right. At this position, and at the corresponding one on the left side, the measuring rod at −60° and −75° could not be used. This procedure was continued until reach along 15° left was measured. This latter position is illustrated in figure 23. All raw data were measured in inches and recorded by hand.**

Twelve anthropometric dimensions were measured on each subject. These are listed below.

Age	Acromion Height, Sitting
Height	Buttock-Knee Length
Weight	Biacromial Diameter
Functional Reach	Shoulder Breadth
Sitting Height	Shoulder-Elbow Length
Eye Height, Sitting	Forearm-Hand Length

The means and standard deviations for these dimensions, as well as comparable data from military and civilian populations are given in Appendix III.

*An anthropometric description of the subjects is included in Appendix III.

**The reach measuring device was designed and fabricated in 1964, before the nationwide shift to the metric system began to receive serious attention.

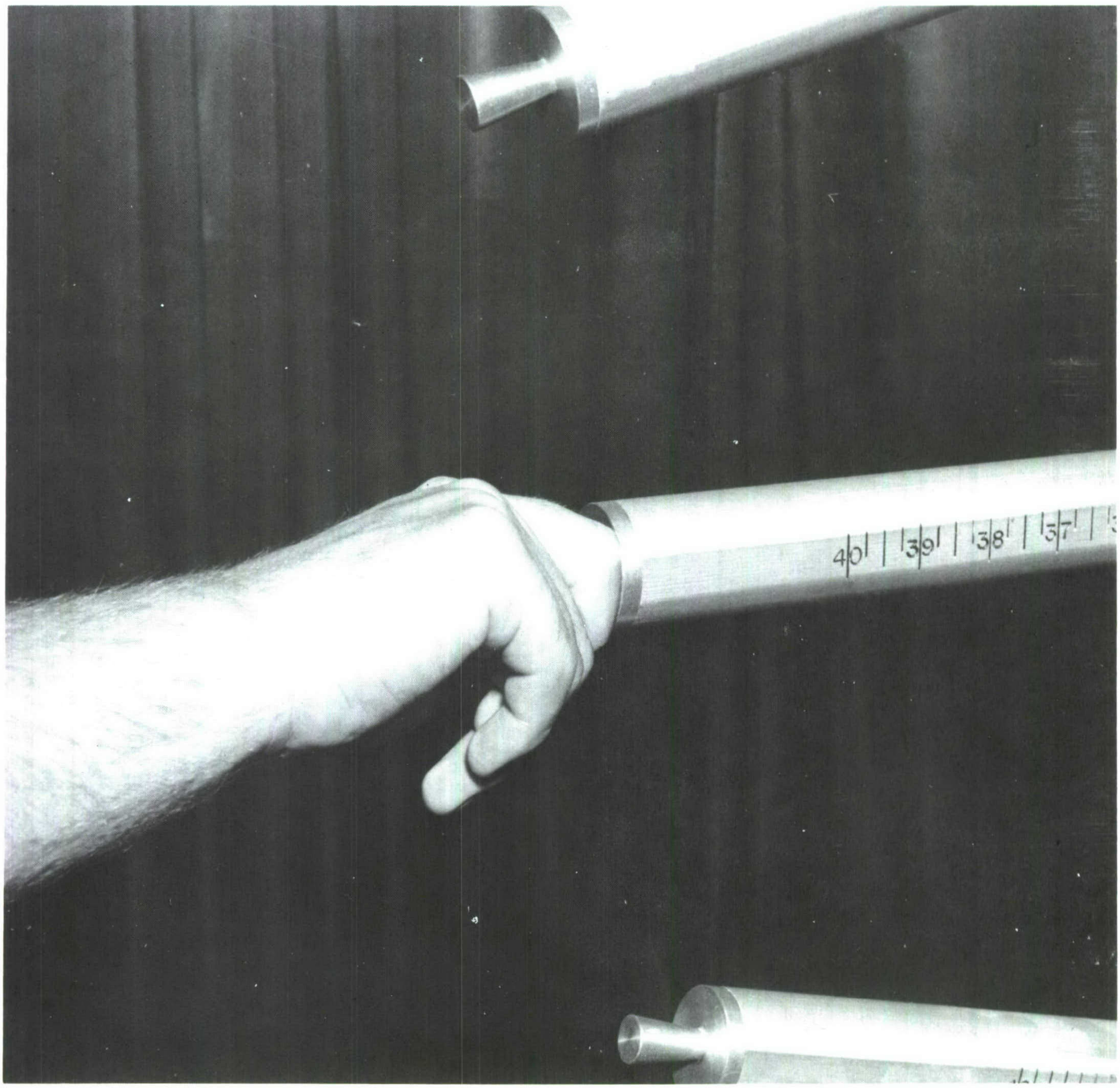

Figure 22. The Thumb-and-Forefinger Grasp. (The reach distance terminated 0.5 inch (1.27 cm) short of the tip of the thumb. This assured that, in applying the data, reach distance is an actual "grasping" distance.

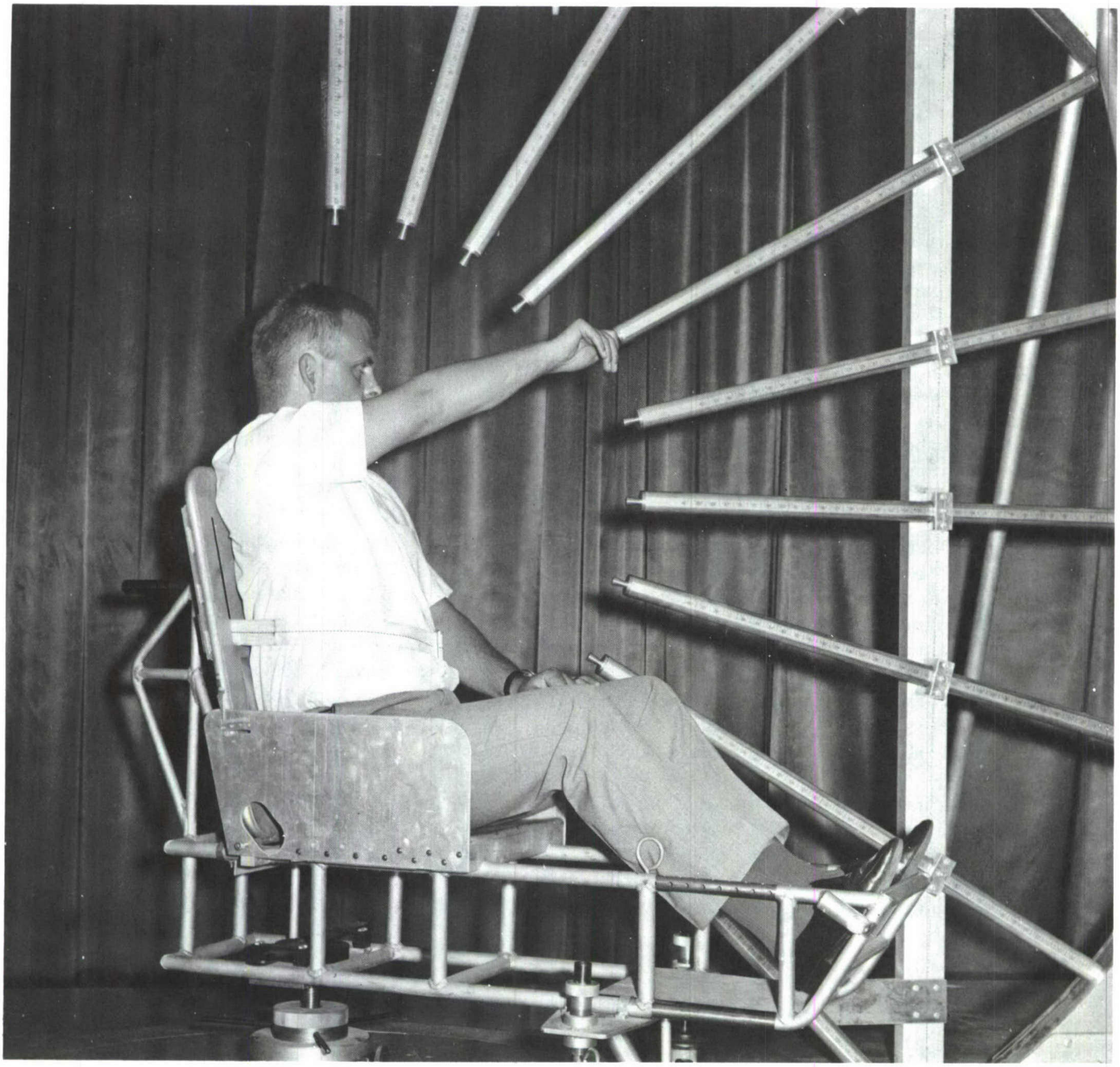

Figure 23. Subject Reaching Along the +30° Vector in the L15° Plane.

METHOD

Reach data were gathered in the form of vertical planes at 15° intervals from a vertical through Seat Reference Point (SRP). They were measured as distances (radii) from a point of origin 24 inches (61 cm) above SRP. Measurements of reach were made to the nearest ¼ inch. Two reach values were obtained for each reach vector, a smaller one, representing the minimum reach distance and a larger value, representing a maximum reach distance. The minimum reach distance may be referred to as the "inside boundary of the reach envelope." Part of the inside boundary is shaped by the surface of the subject's body and of the chair in which he sits. They form obstructions which, in effect, are impressed into the reach envelope. The inside boundary is also determined, in part, by the combined limits to mobility at the shoulder, elbow, and wrist.

The maximum reach distance may be referred to as the "outside boundary of the envelope." Its size and shape are determined by such factors as the length of the arm, mobility of the joints involved, the extent to which the subject might be able to lunge in the direction of reach, and the size of the torso around which he must reach. Chaffee (1969) also cites clothing and psychological motivation as affecting reach capability.

To repeat: the purpose of this research is to derive the complete, 3-dimensional, 5th, 50th, and 95th percentile grasping-reach envelopes of men and women, for the seated operating position, that would be readily usable by engineers and designers to locate positions for critical hand-operated controls in machine and vehicle operating compartments. The 5th percentile envelope, a small reach envelope, is intended to be of such a size that 95 percent of the adult using population will be able to reach to or beyond its boundary. Similarly, the 50th and 95th percentile envelopes are intended to be of such sizes that 50 and 5 percent, respectively, can reach to or beyond their limits.

Tall people are generally considered to have greater reach capability than short people, especially with regard to the outer boundaries of reach envelopes. When the inside boundaries of percentile reach envelopes are considered, factors other than body lengths must also be considered. The major surface area of the inside boundary of a given reach envelope is determined by more than the length of the arm. The thickness and shape of the torso is also of significant importance. It follows that an individual with a large, broad torso will not be able to reach as far inward as an individual with a small, narrow torso. Consequently, greater reach capability is influenced not only by arm length, but also by torso size and shape. For these reasons, the outside and inside boundaries of the percentile envelopes had to be determined in exactly opposite fashions.

To determine the outer boundaries of the 5th, 50th, and 95th percentile envelopes, the values for all maximum reach distances were assembled and listed in ascending order of value. Reach values for male and female subjects were listed separately.* Since the full complement of values was 30, the 2nd value was selected and designated the 5th percentile value; the average of the 15th and 16th values was determined and designated the 50th percentile; the 29th value was designated the 95th percentile value.

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*See Appendix II for tabular data describing reach envelopes for 50/50 Male-Female populations.

To determine the inner boundaries of the various percentile envelopes, the values for all minimum reach distances were also listed in ascending order of value. In this listing the designation of percentiles was opposite for the outer boundary and the 5th and 95th percentile values each are taken from opposite ends of the range.*

Because all subjects do not have the same mobility characteristics, there were angles along which some or all could not reach. Therefore, it was not possible to list a complete set of 30 values for all angles. When there were fewer than 29 values, the reach angle in question was not within the 5th percentile reach envelope. If there were fewer than 15 or two values for any given reach angle, that angle was not within the 50th or 95th percentile envelopes, respectively.**

On listing the percentile outer and inner boundary values of a given vector, occasionally the value from the maximum reach list was less than that from the minimum list. This possibility arises because, although the two listings are related, they are relatively independent of each other. There is no great relationship between the maximum and minimum reaches for any given subject. In addition, the least value from the list of outer boundary values cannot be expected to be larger than the greatest value in the list of inner boundary values. When this occurred, both values were discarded. The subject order cannot be expected to be symmetrical between listings of inner and outer boundary values.

In determining prcentile values below, say, the 15th and above the 85th from their rank order in a small series, some irregularity and a somewhat questionable accuracy are expected. The distribution of values for any given reach angle, while not normally distributed, is somewhat concentrated toward the middle of the range. Therefore, the interval between values at the ends of the distribution will inevitably be greater than for those toward the center. The greater interval between values at the ends of the distribution leads to inaccuracies in selecting the very percentiles (especially the 5th) which are of greatest value in design. It was necessary, therefore, to resort to a data smoothing routine. This technique is based on the rather straight-forward logic that most of the outside "surface" of the reach envelope is smooth and regular; i.e., over most of the outside surface of a reach envelope, an extraneous depression or elevation is not usually found. Further, for the forward and upper half and for the right side, the radii of the outer surface of the envelopes change in an orderly, gradual, and often predictable fashion. For the left-rear sectors of the reach envelopes these premises do not hold up as well because, to reach into this region, one's torso and head become obstructive and the manner in which the subject reached around them was difficult to control. In addition, the subjects' ability to manipulate the measuring rods in this sector appeared to be degraded. They sometimes lost their ability to distinguish the appropriate direction of arm and hand movements to operate the measuring rods. In order words, they were in unfamiliar territory.

The data smoothing technique entailed the elimination of extraneous and unaccountable irregularities in the surface of each envelope contour and was carried out as follows. Raw data were initially plotted on representations of the vertical planes through SRP (see figure 24). Once the smoothing was completed for these vertical planes, the partially smoothed envelopes were replotted as horizontal (X-Y) contours at 6-inch intervals above and below SRP, similar to those of figures 25 through 30. This was accomplished by taking horizontal measurements from the SRP-V at each 6-inch level within all partially smoothed vertical planes, and replotting these data along the appropriate

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*Because the distribution of reach data along the reach angles is not normal and because many reach angles were reachable by less than a full complement of 30 subjects, statistical processes applying to the normal distribution could not be used. Therefore, the percentile values could not be accurately determined through the use of the mean and standard deviation, as is so often used. Placement in rank order appeared to be the most appropriate technique.

**On the occasions when there was a full complement of 30 values, the means and standard deviations were calculated and reported.

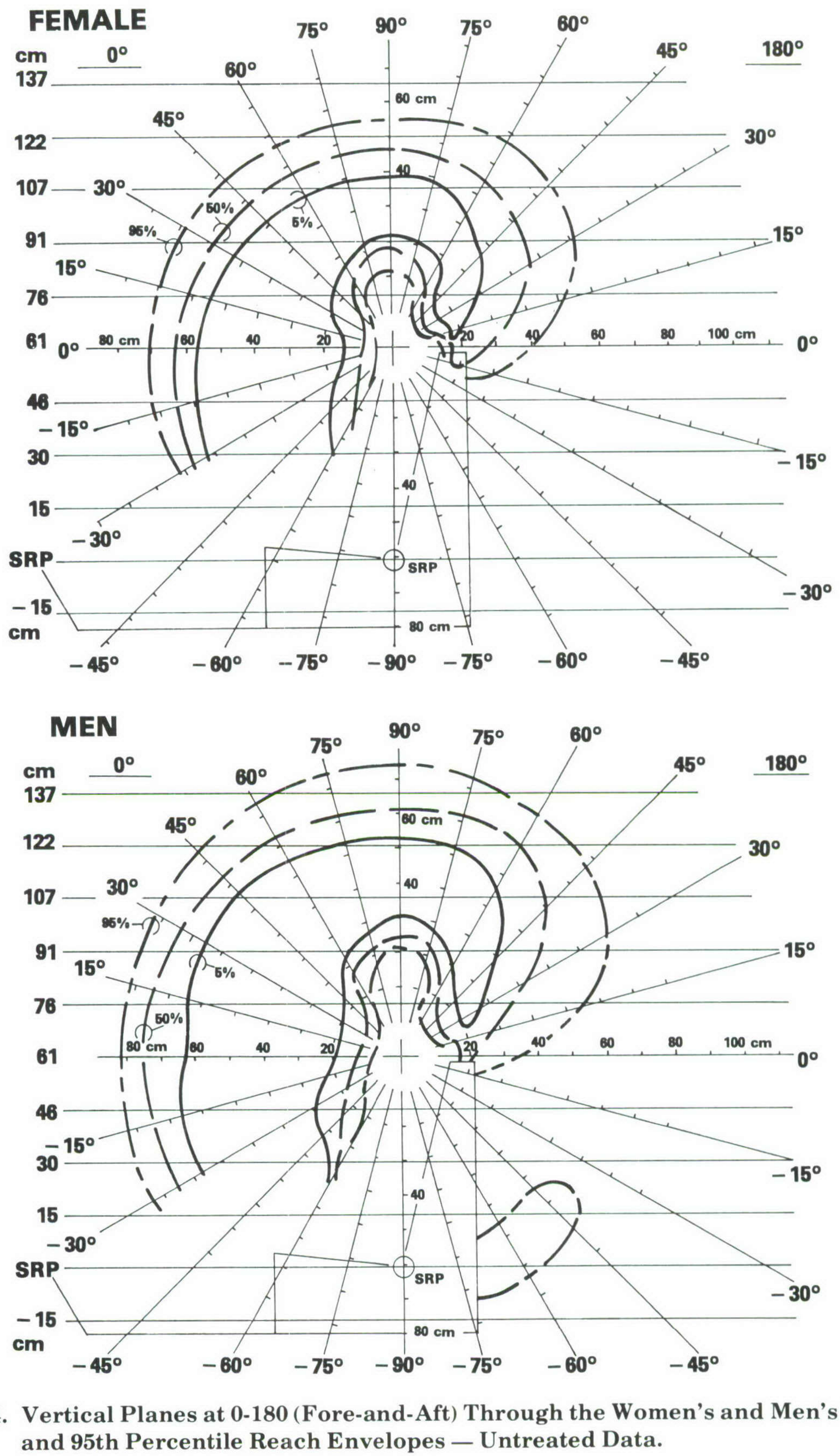


Figure 24. Vertical Planes at 0-180 (Fore-and-Aft) Through the Women's and Men's 5th, 50th, and 95th Percentile Reach Envelopes — Untreated Data.

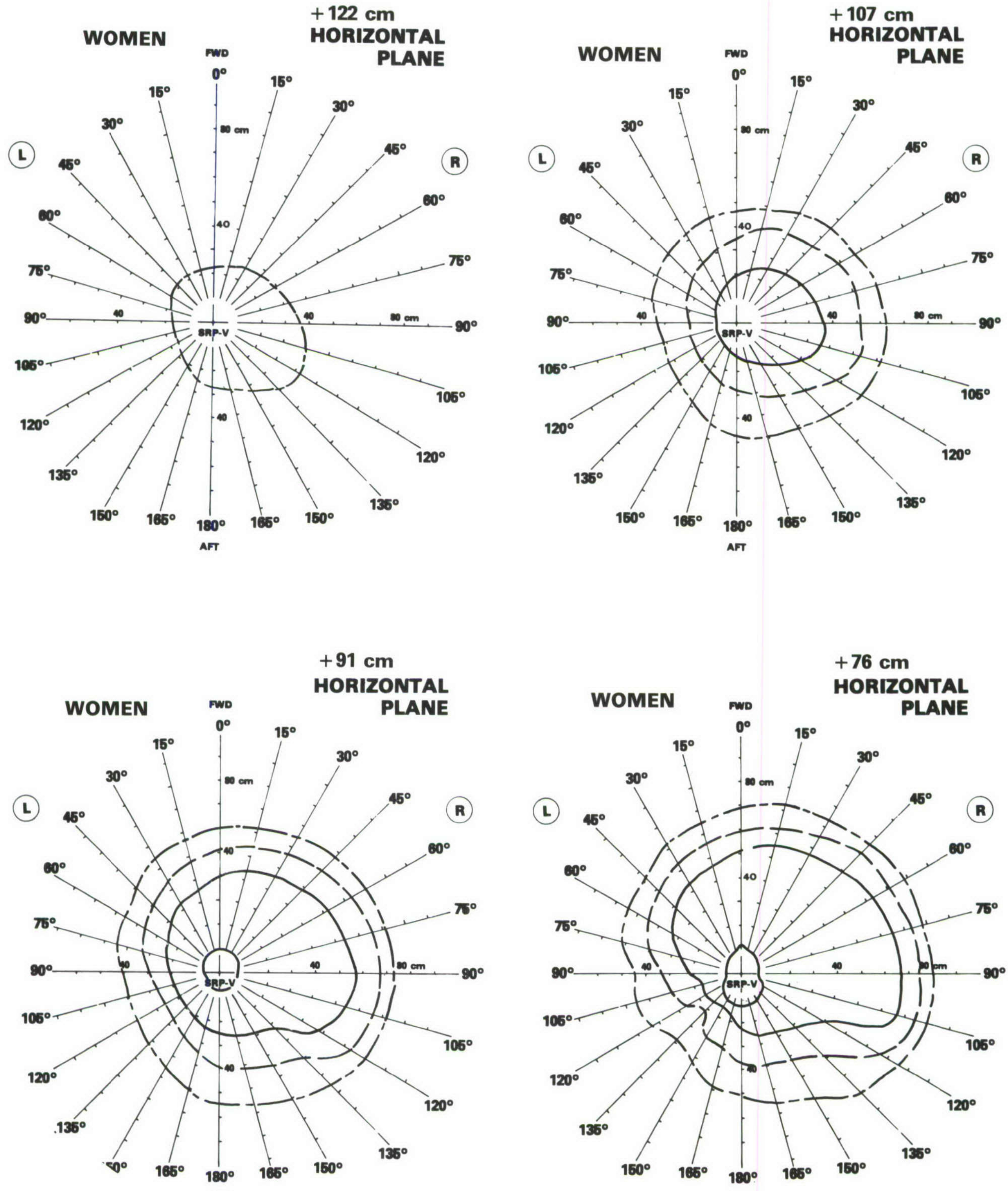


Figure 25. Horizontal Planes Through the 95th Percentile Envelope at 122 cm Above SRP and Through the 5th, 50th, and 95th Percentile Envelopes at 107, 91, and 76 cm.

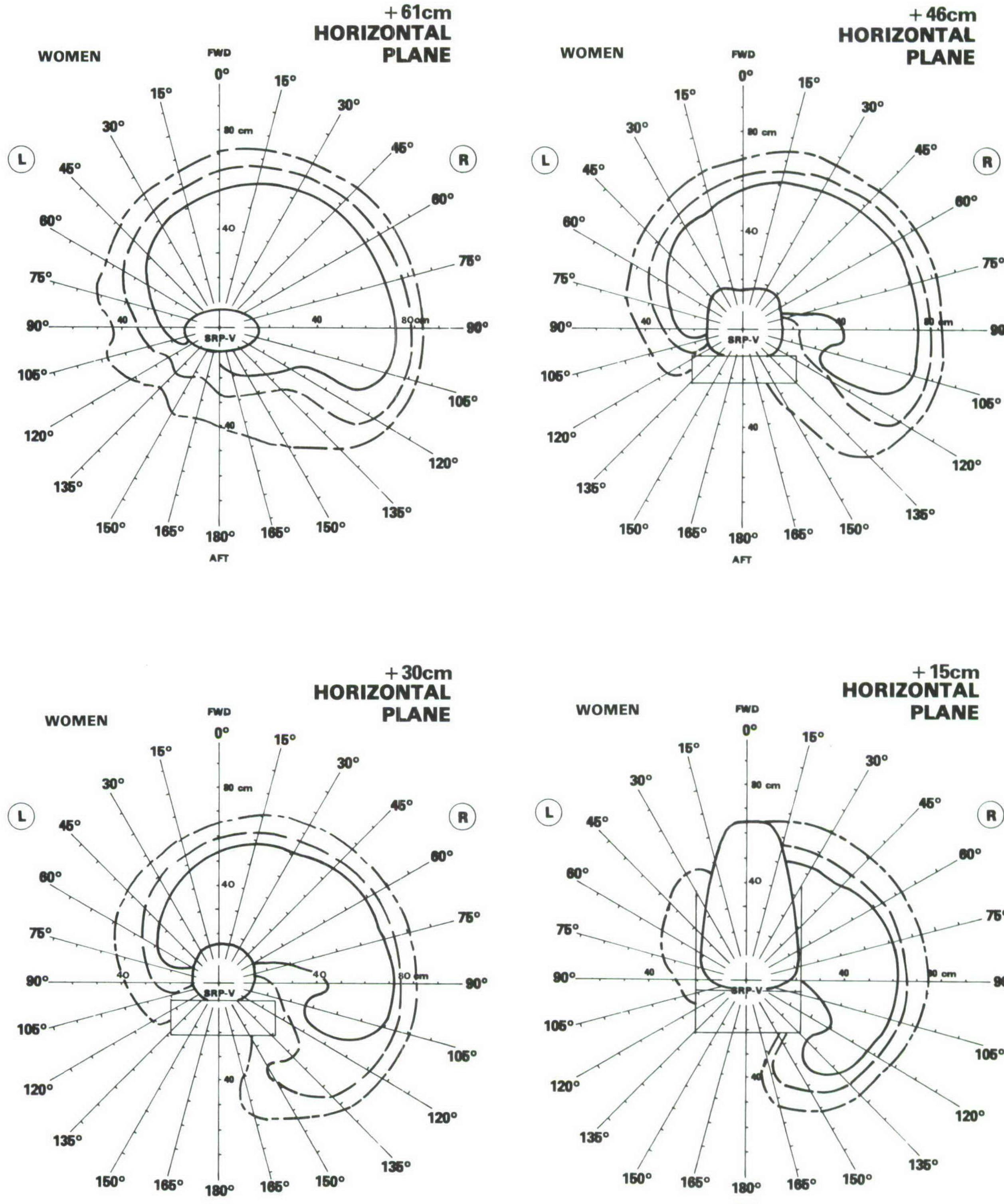
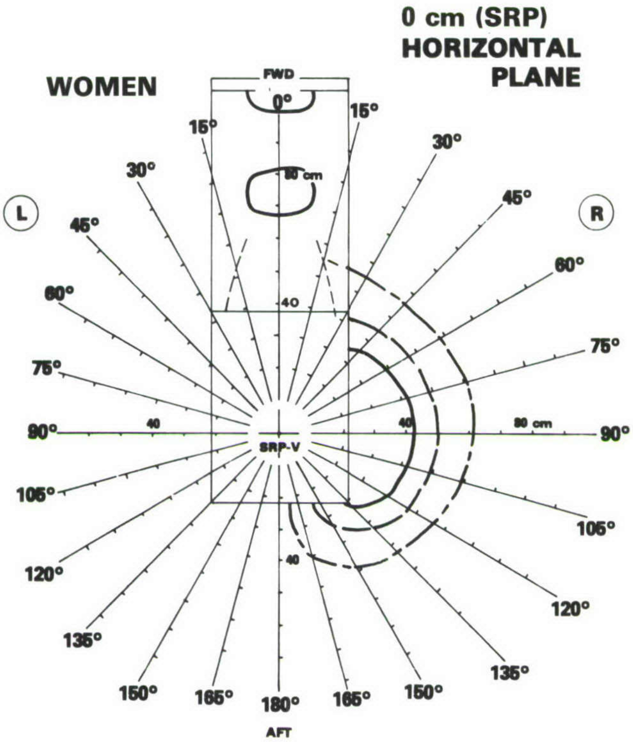


Figure 26. Horizontal Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at 61, 46, 30, and 15 cm Above SRP — Women.



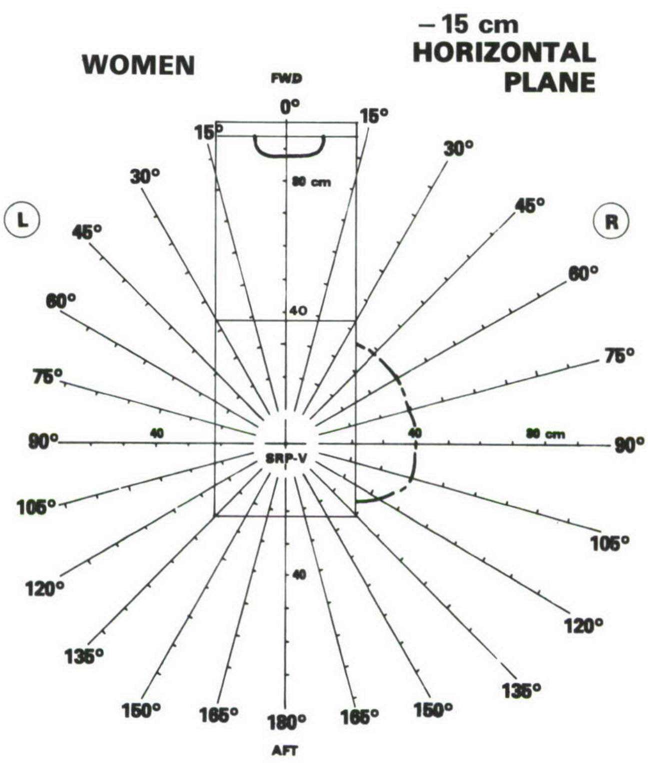


Figure 27. Horizontal Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at SRP Level and Through the 95th Percentile Reach Envelope at 15 cm Below SRP — Women.

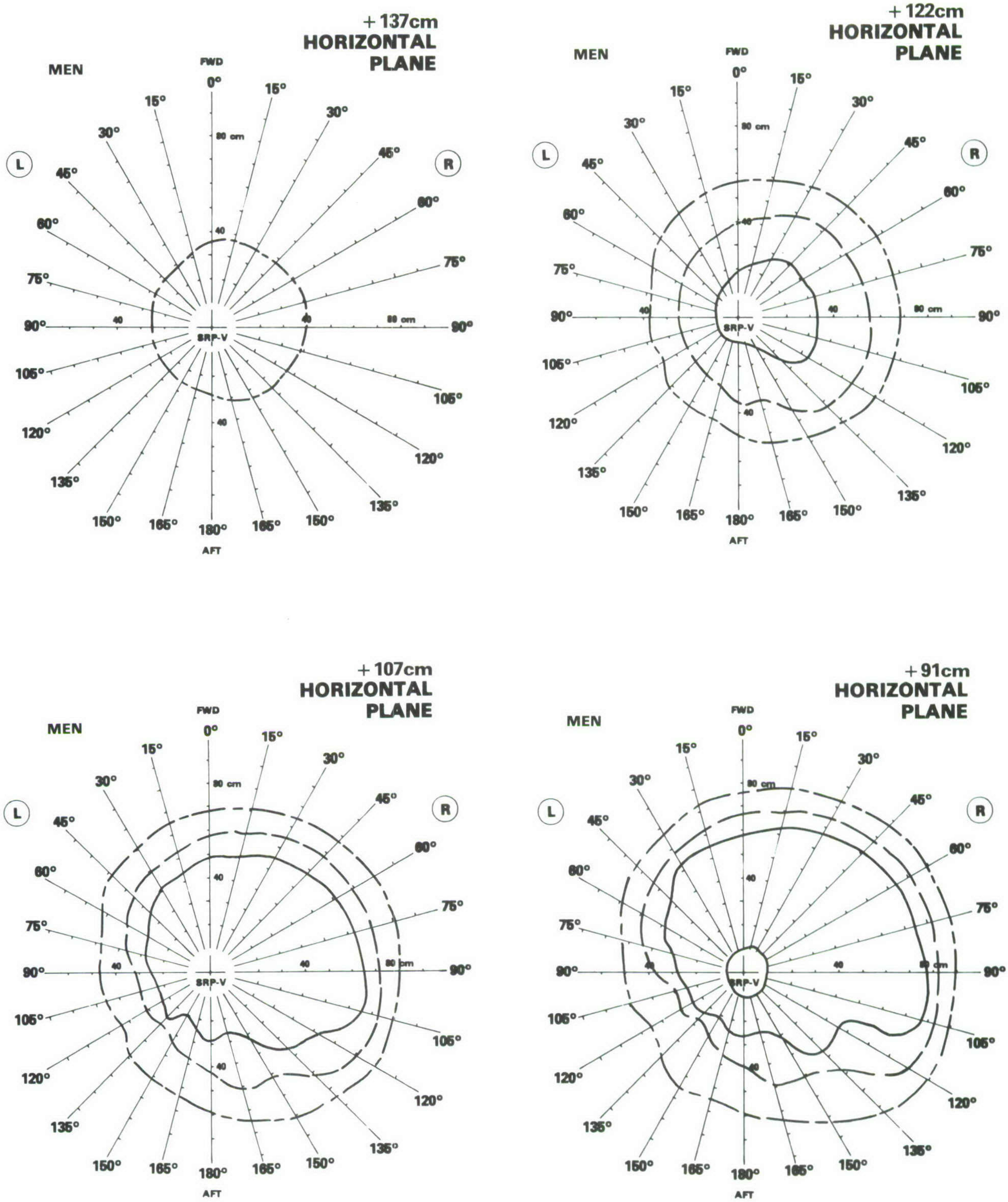


Figure 28. Horizontal Planes Through the 95th Percentile Reach Envelope at 137 cm above SRP and the 5th, 50th, and 95th Percentile Reach Envelopes at 122, 107, and 91 cm Above SRP — Men.

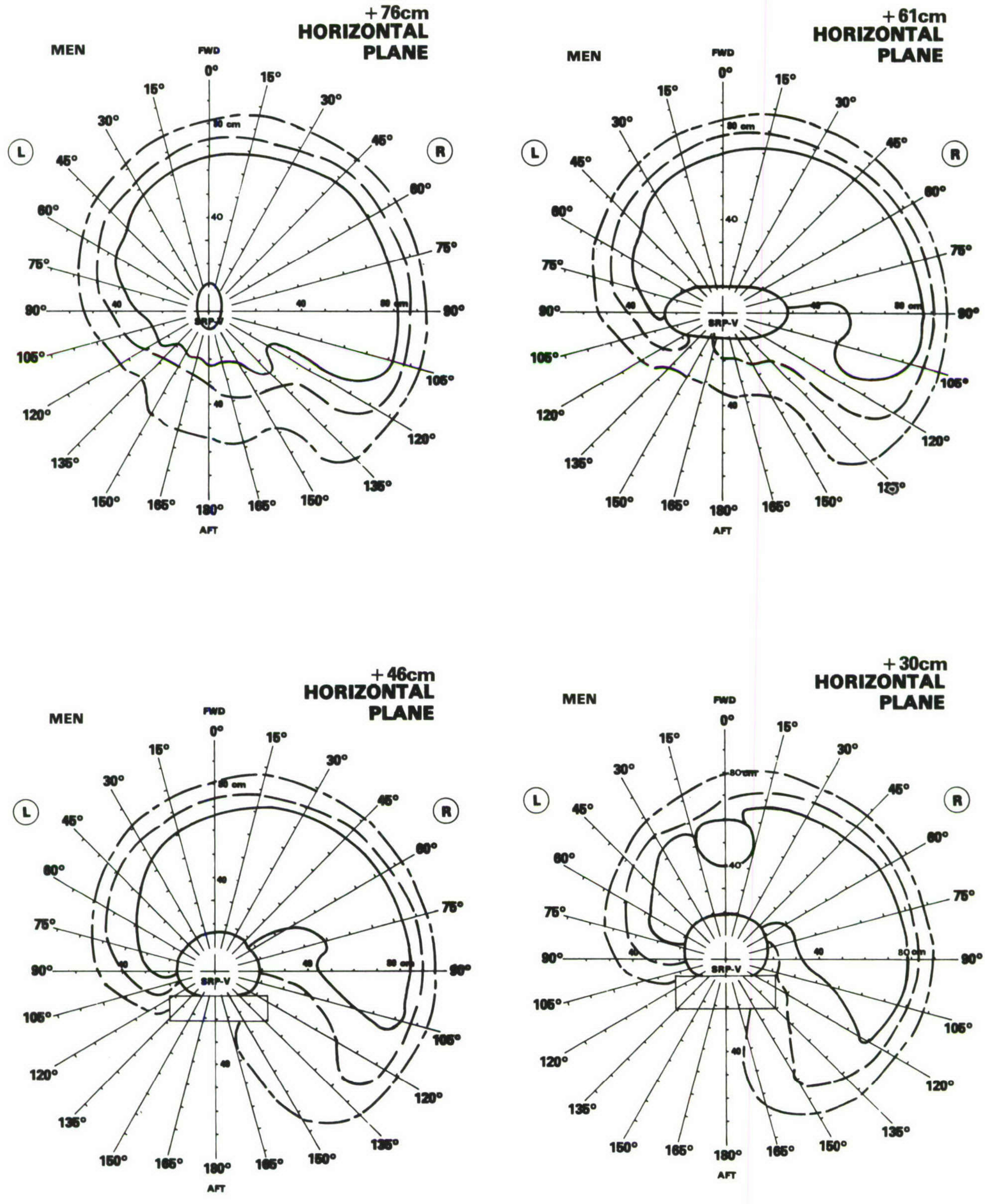


Figure 29. Horizontal Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at 76, 61, 46, and 30 cm Above SRP — Men.

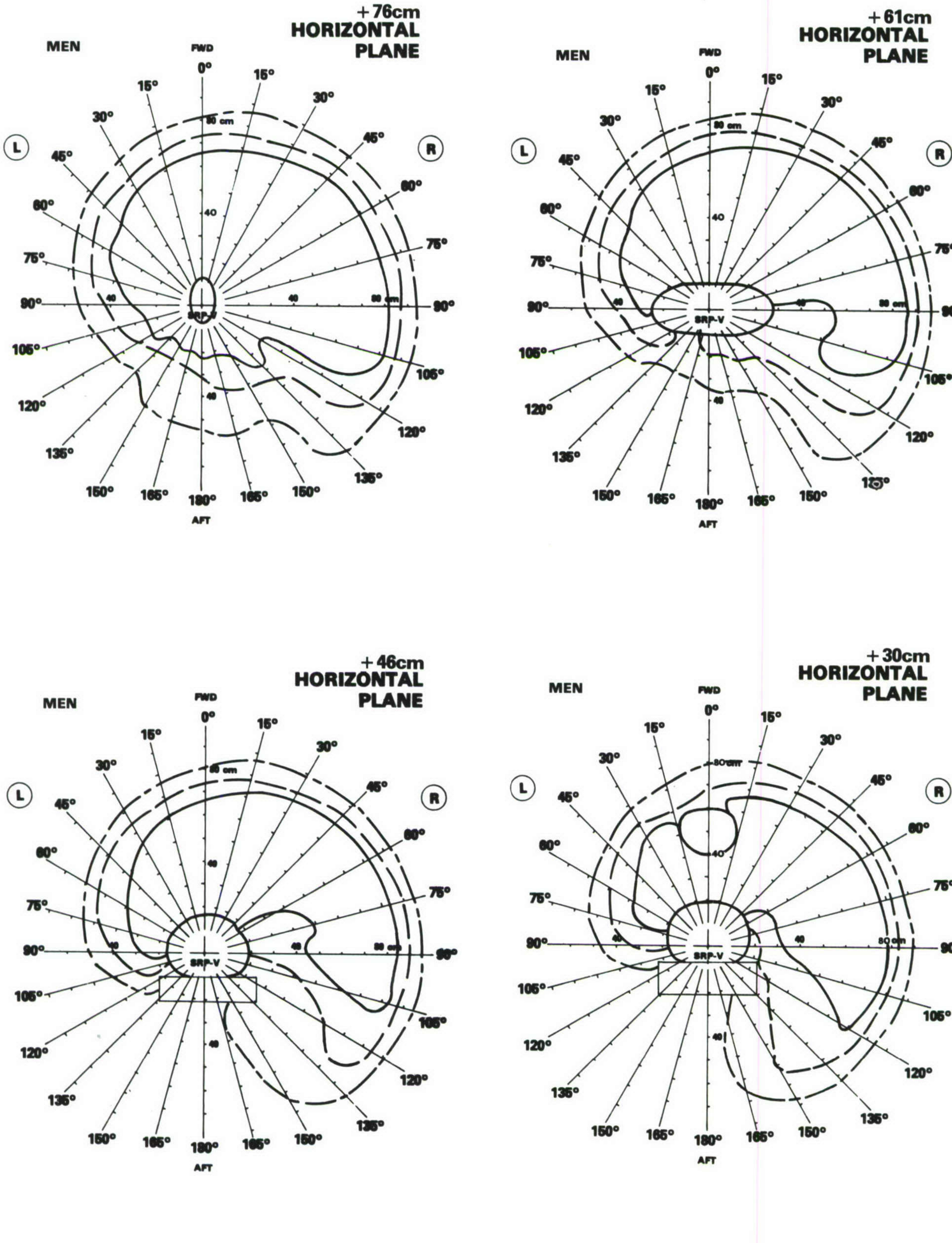


Figure 29. Horizontal Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at 76, 61, 46, and 30 cm Above SRP — Men.

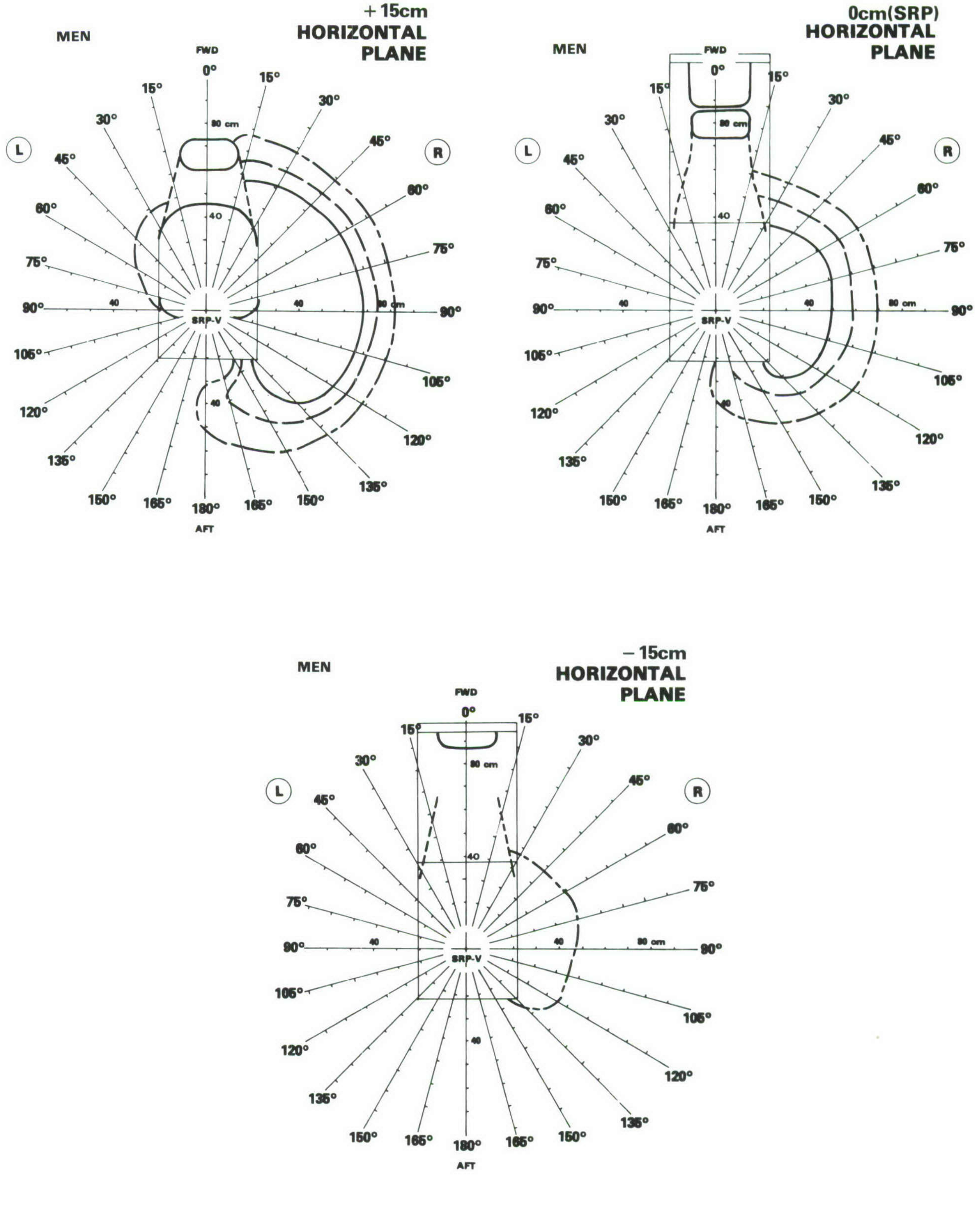


Figure 30. Horizontal Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at 15 cm Above SRP and at SRP Level and Through the 95th Percentile Reach Envelope at 15 cm Below SRP — Men.

angles in the various horizontal planes. The smoothing procedure was applied to these horizontal planes and agreement was achieved with the initial vertical planes. If agreement could not be achieved, the irregularity was assumed to be real. Once the smoothing process was completed on the horizontal contours (and the original vertical planes at 15° intervals), parallel lines were drawn at 6-inch intervals from SRP on each to represent frontal (Y-Z) planes. Distances from the midsagittal plane (0°-180°), right and left to the envelope boundaries, were extracted and frontal planes were drawn similar to those in figures 31 through 35. After the frontal planes were smoothed and justified with the horizontal and original vertical planes at 15° intervals, parallel lines at 6-inch intervals were again drawn on the same horizontal (X-Y) contours, but perpendicular to those representing frontal (Y-Z) planes. These new lines, then, represented parasagittal (X-Z) planes. Distances from the primary frontal plane (L90°-R90°) to the envelope boundaries were measured and replotted to yield vertical fore-and-aft (X-Z) planes similar to those illustrated in figures 36 through 41. Again, all smoothing decisions were justified with the horizontal contours and the original vertical planes at 15° invervals. As would be expected, the occasions in which it was necessary to smooth the data were fewer and fewer as the smoothing process continued. When completed, the process yielded smoothed horizontal (X-Y) contours, vertical planes at 15° intervals around SRP-V*, vertical (Y-Z) planes, and vertical (X-Z) planes.

Note: Conversion to the metric system was not accomplished until after the data smoothing routines were completed. Since reach was reported to the nearest 1/4 inch (0.635 cm), all data were converted to the nearest centimeter.

Tabular data describing sections through the various envelopes follow the figures.

For a comparison between selected final data and the original, see Appendix I.

Most of the inner boundary data were not subjected to the smoothing routine, since, for the most part, its surface coincided with that of the body and chair. On plotting the raw data as vertical planes at 15° intervals through SRP-V, however, a problem became evident with regard to the usefulness of that portion of the inner boundary describing the surfaces of the upper torso and head. Because of differences in body size, the irregularity with which subjects were willing to pull the measuring rods to the surface of their bodies, and the occasional tendency to dodge the measuring rod as the subject pulled it toward his head, there was greater variability among these values than expected. An example of these preliminary vertical planes is shown in figures 24 and 25. As can be seen, the range of values betwen the 5th and 95th percentiles for upper body surface measurements is quite large. Because of this excessive variability, the original data were not useful in describing the surface of the body. They were useful, however, in defining that portion of the inner boundary resulting from limitations of limb mobility and the manner in which the inner boundary intersected the surface of the body and the seat.

To provide information about size and shape of the seated human form, I decided to use 95th percentile body measurements for each, the men and the women, and substitute a three-dimensional rendition of these data as part of the inner boundary of the reach envelopes. Anthropometric data were taken from Hertzberg, Daniels, and Churchill (1954), Clauser et al. (1972), Grunhofer and Kroh (1975), and Garrett and Kennedy (1971).

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*Vertical planes at 15° intervals are not included in this report. While they are extremely useful in evaluating the placement of controls, they are difficult to visualize for the purpose of design.

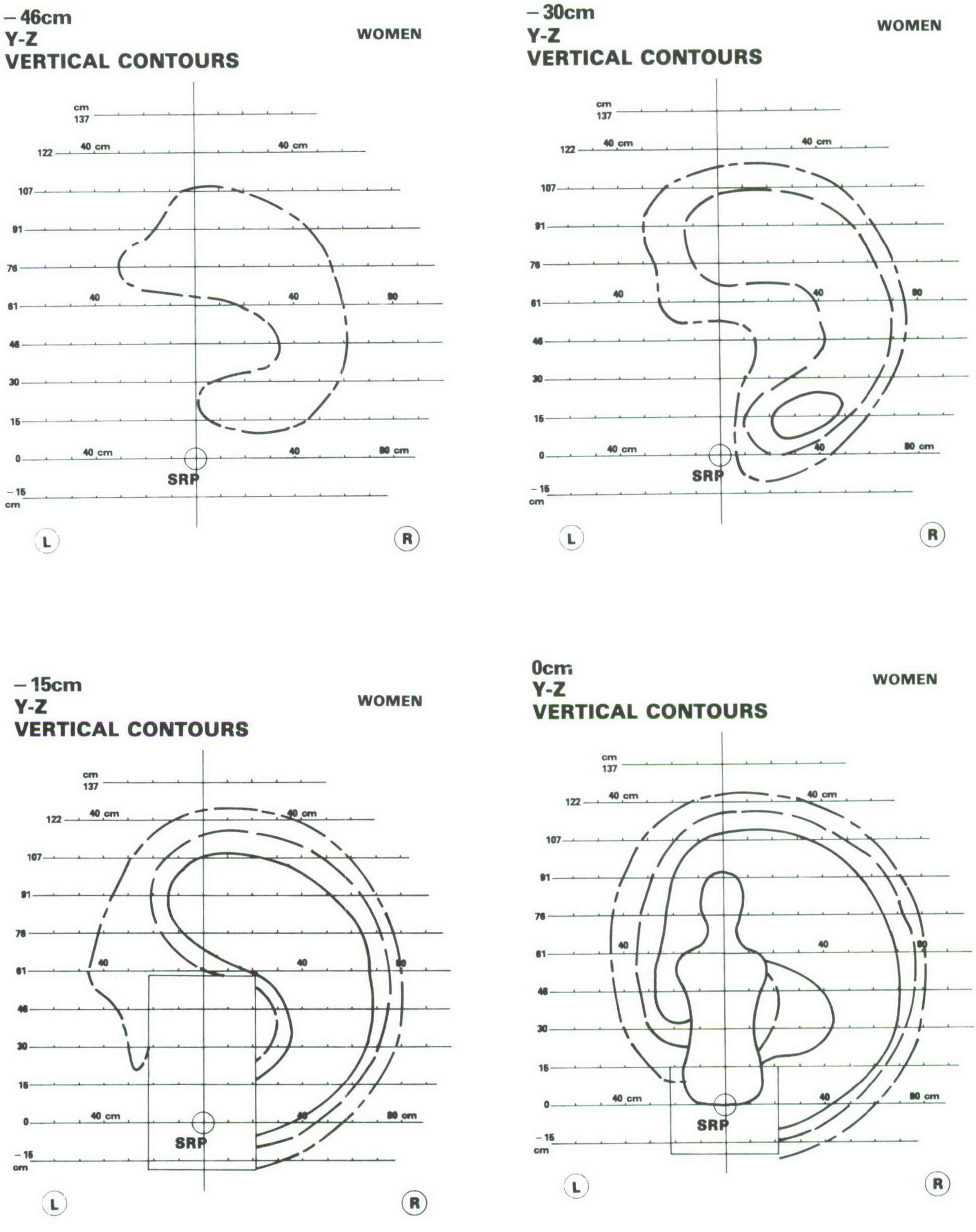


Figure 31. Vertical (Y-Z) Planes Through the 95th Percentile Reach Envelope at −46 cm (Aft) from SRP and Through the 5th, 50th, and 95th Percentile Envelopes at −30, −15 cm (Aft) and at SRP — Women.

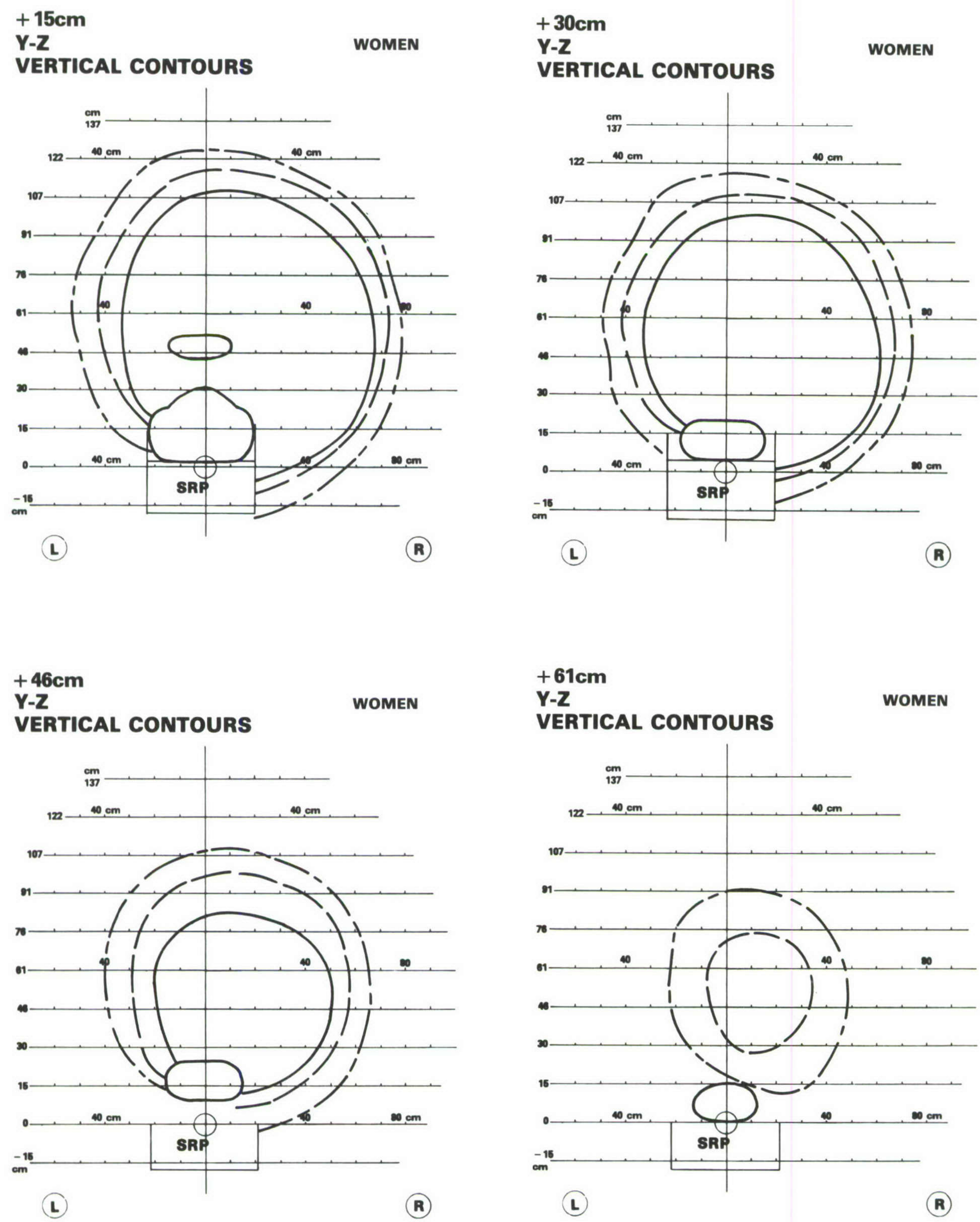


Figure 32. Vertical (Y-Z) Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at +15, +30, and +46 cm (Fwd) from SRP and Through the 50th and 95th Percentile Envelopes at +61 cm (Fwd) from SRP — Women.

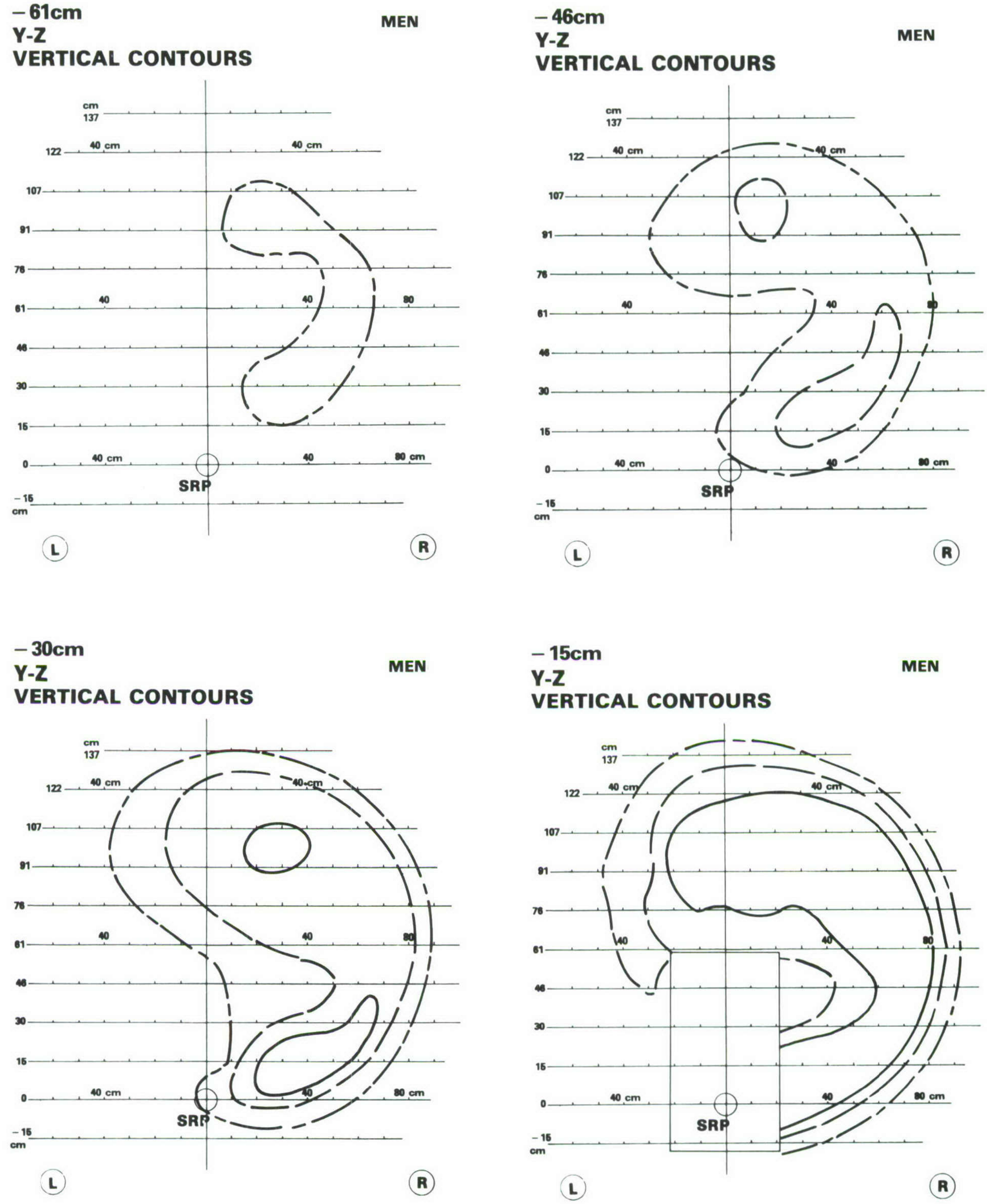


Figure 33. Vertical (Y-Z) Planes Through the 95th Percentile Reach Envelope at –61 cm (Aft) from SRP, Through the 50th and 95th Percentile Envelopes at –46 cm (Aft) from SRP, and Through the 5th, 50th, and 95th Percentile Envelopes at –15 cm (Aft) and at SRP — Men.

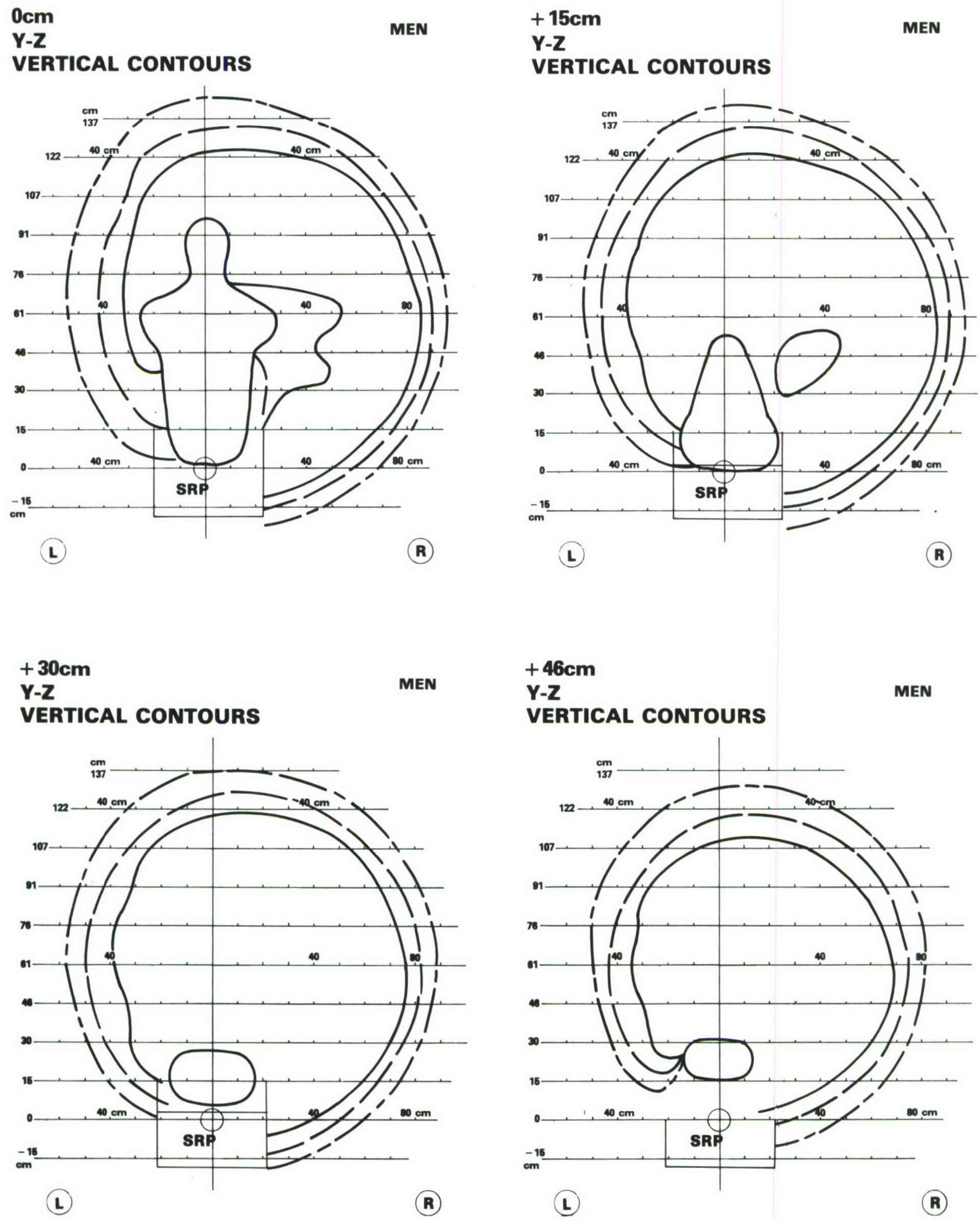
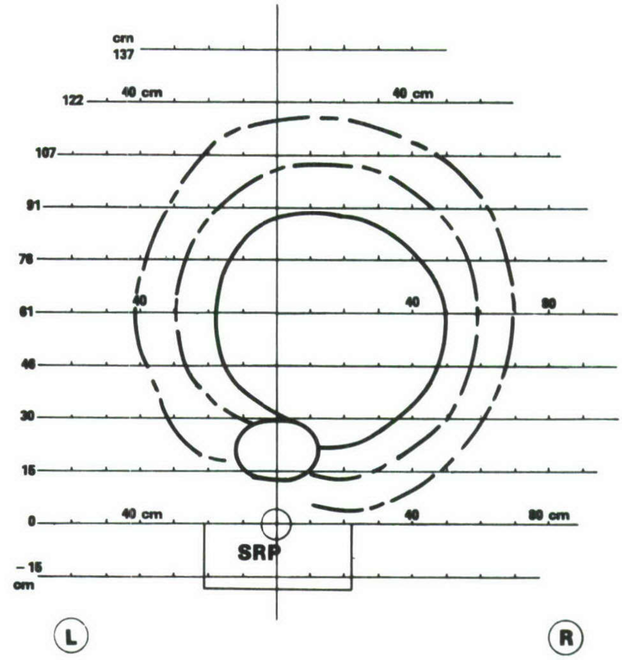


Figure 34. Vertical (Y-Z) Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at SRP, +15, +30, and +46 cm (Fwd) from SRP — Men.

+61cm
Y-Z
VERTICAL CONTOURS

MEN



+76cm
Y-Z
VERTICAL CONTOURS

MEN

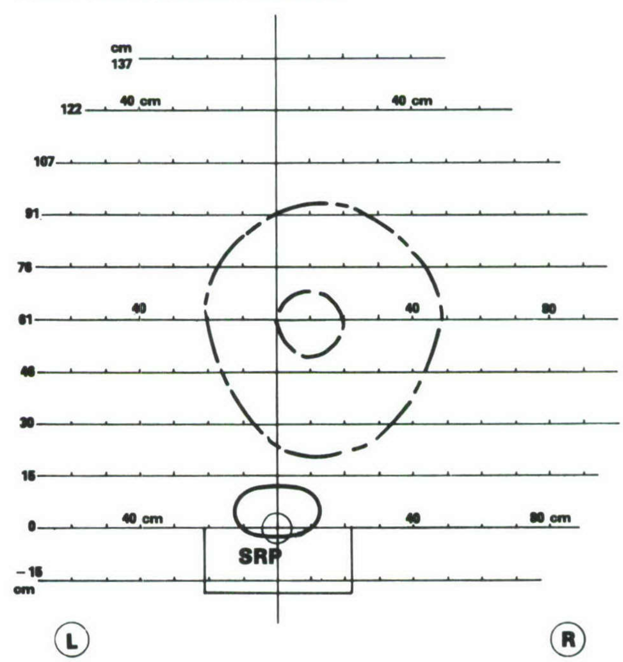


Figure 35. Vertical (Y-Z) Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at +61 cm (Fwd) from SRP and Through the 50th and 95th Percentile Envelopes at +76 cm (Fwd) from SRP — Men.

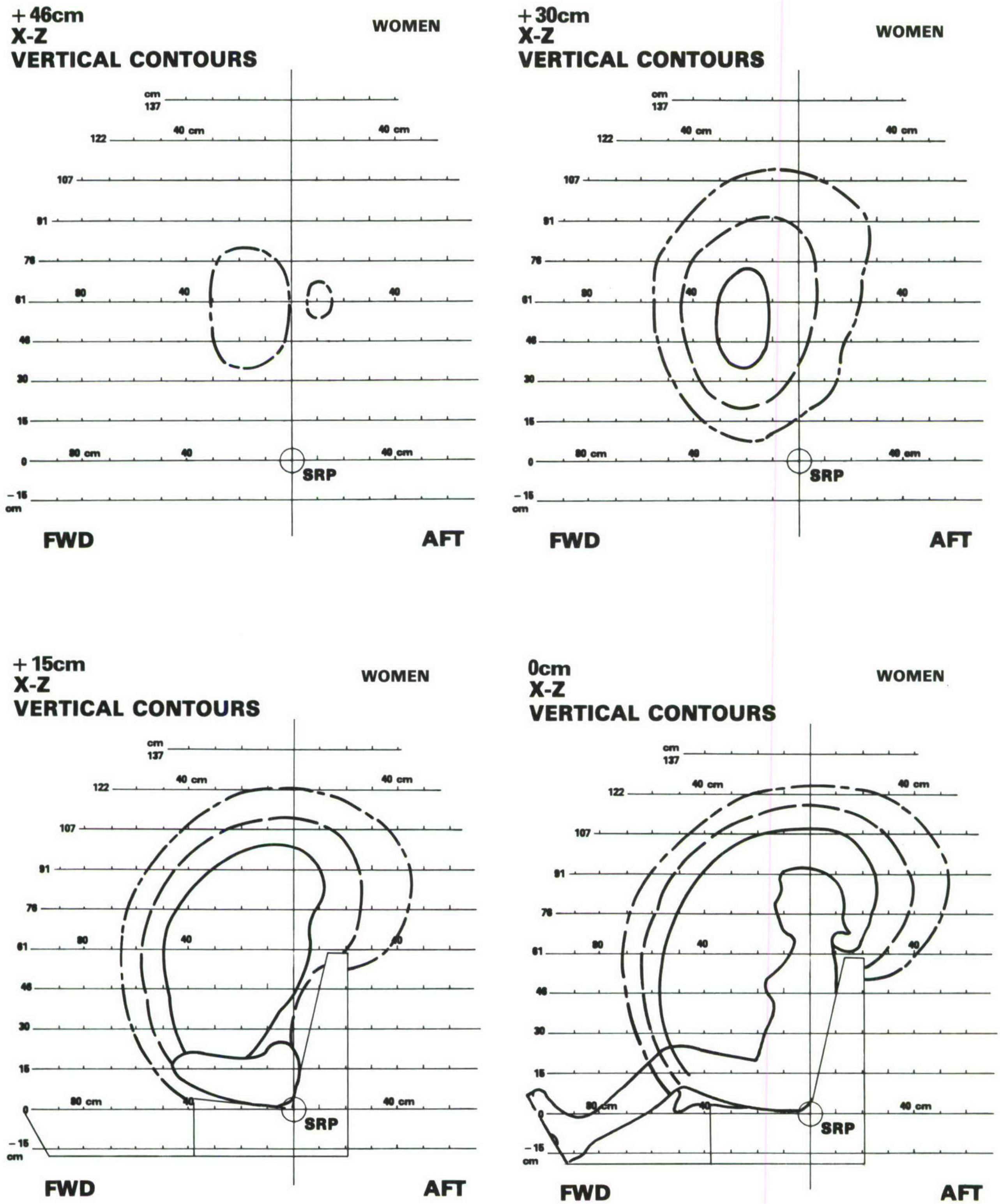


Figure 36. Vertical (X-Z) Plane Through the 95th Percentile Reach Envelope at +46 cm (Left) from SRP and Through the 5th, 50th, and 95th Percentile Envelopes at +30, +15 (Left) and at SRP — Women.

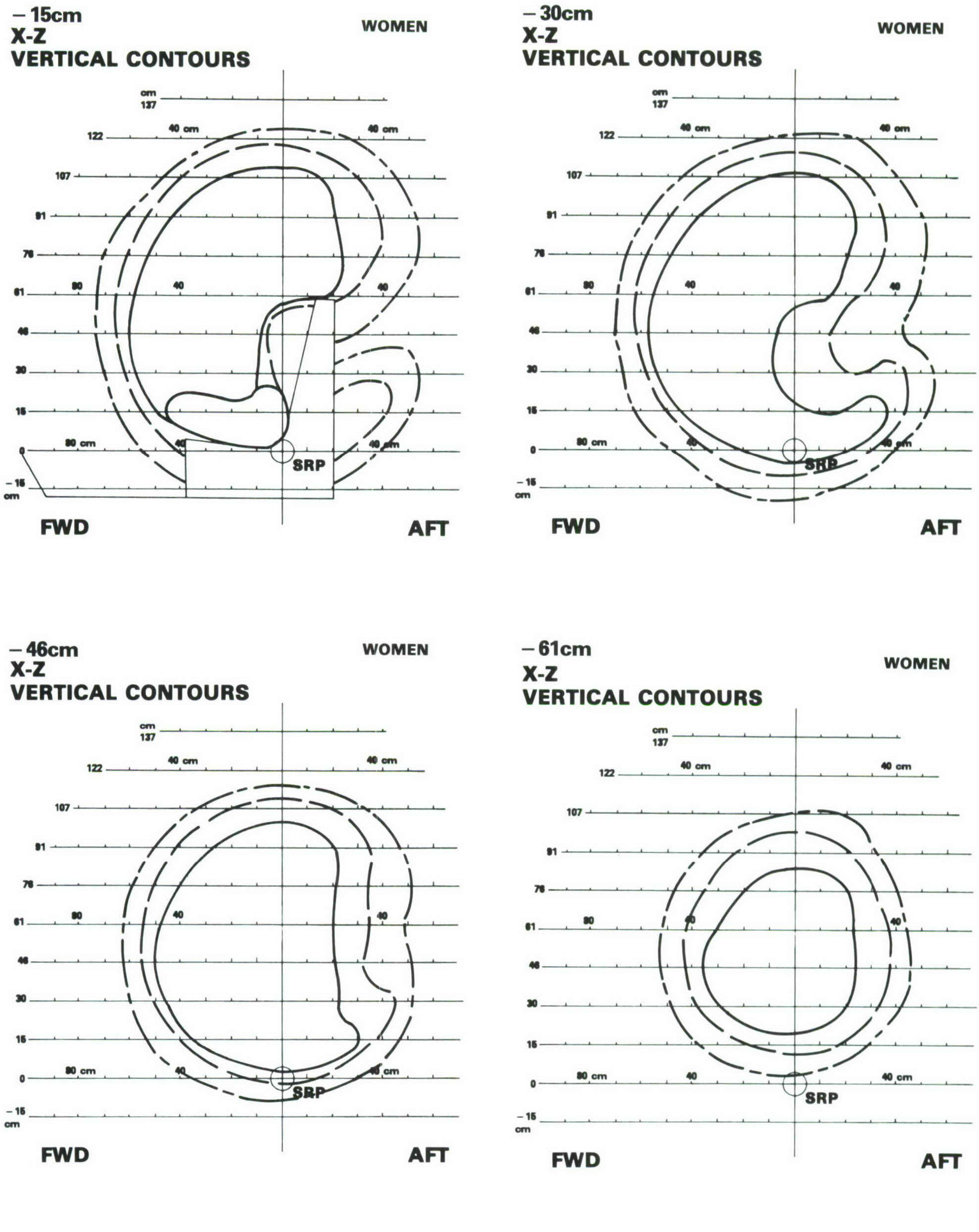


Figure 37. Vertical (X-Z) Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at −15, −30, −46, and −61 cm (Right) from SRP — Women.

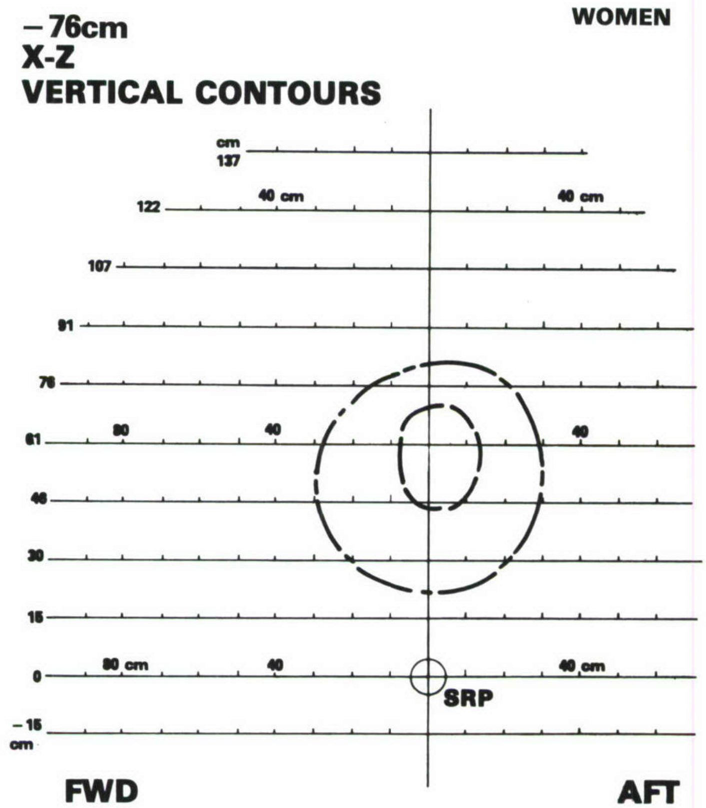


Figure 38. Vertical (X-Z) Plane Through the 50th and 95th Percentile Reach Envelopes at −76 cm (Right) from SRP — Women.

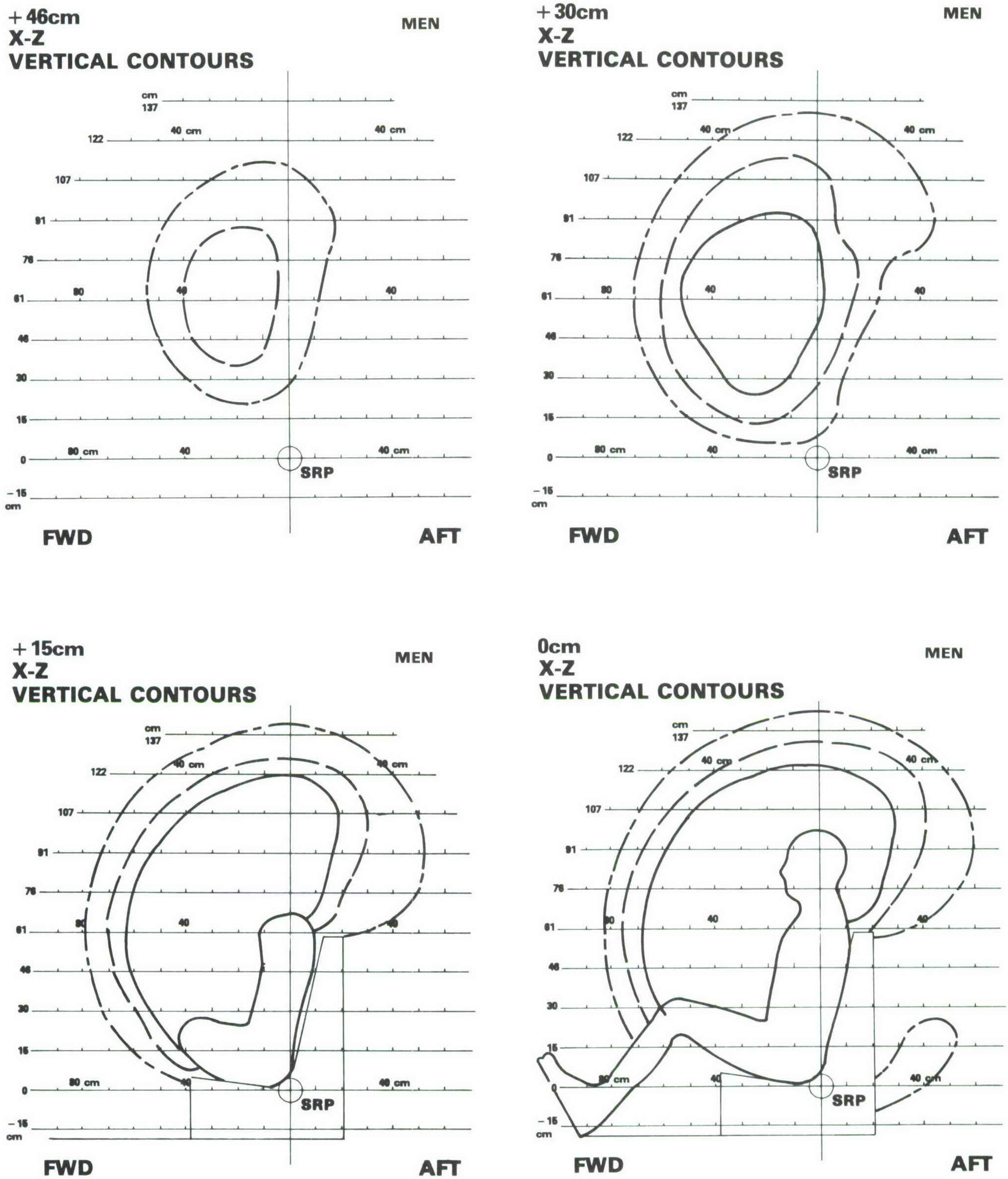


Figure 39. Vertical (X-Z) Planes Through the 50th and 95th Percentile Reach Envelopes at +46 cm (Left) from SRP and Through the 5th, 50th, and 95th Percentile Envelopes at +30, +15 (Left) and at SRP — Men.

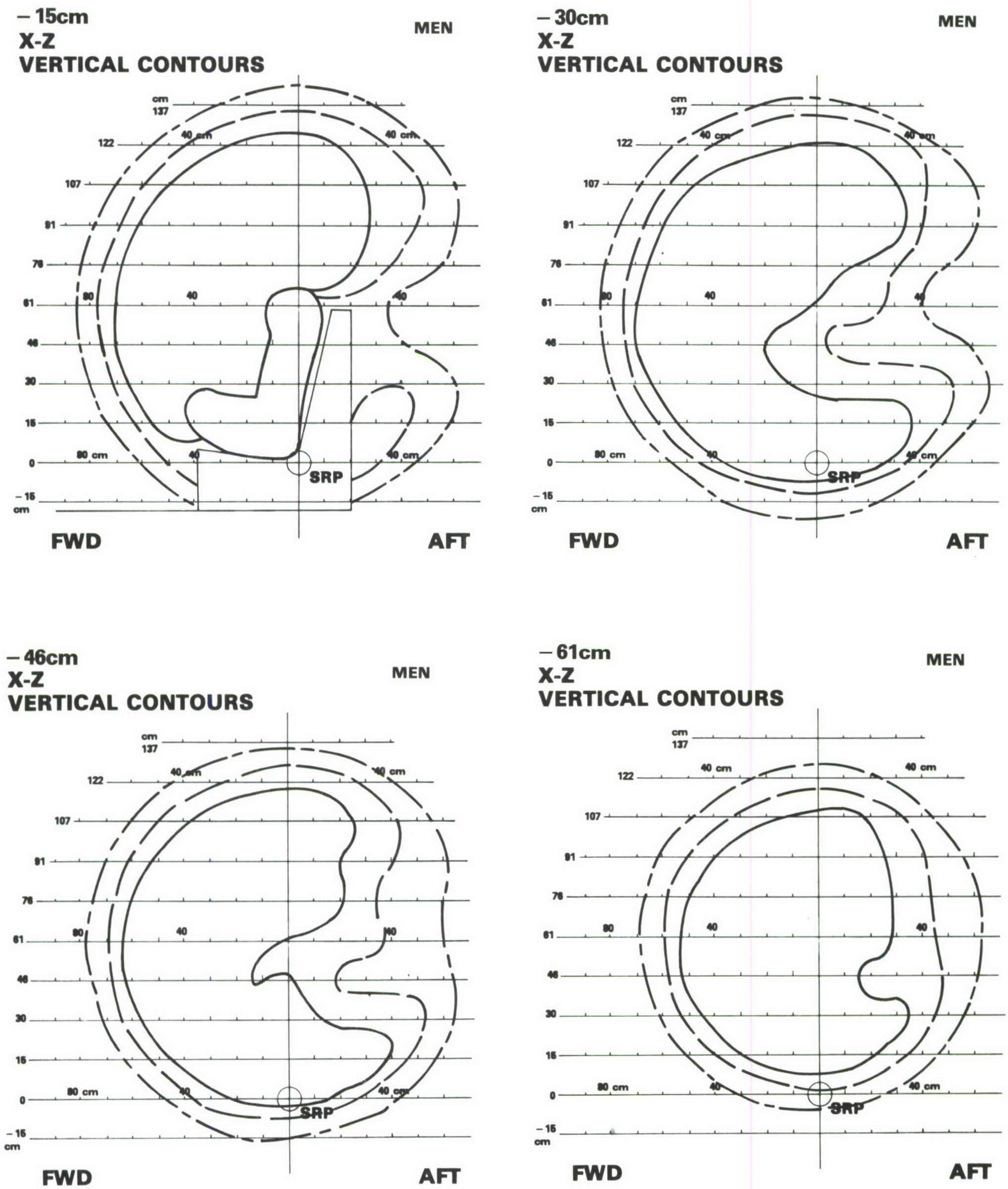
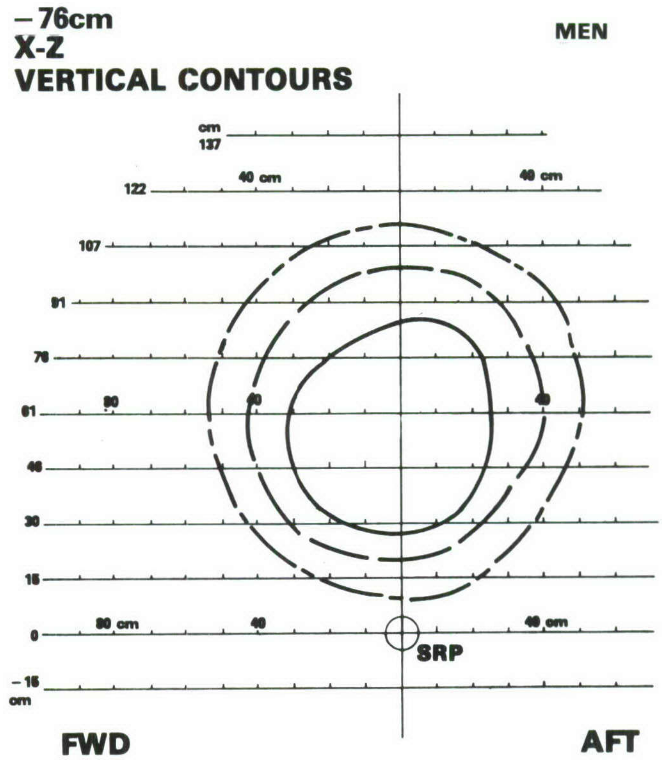


Figure 40. Vertical (X-Z) Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at −15, −30, −46, and −61 cm (Right) from SRP — Men.



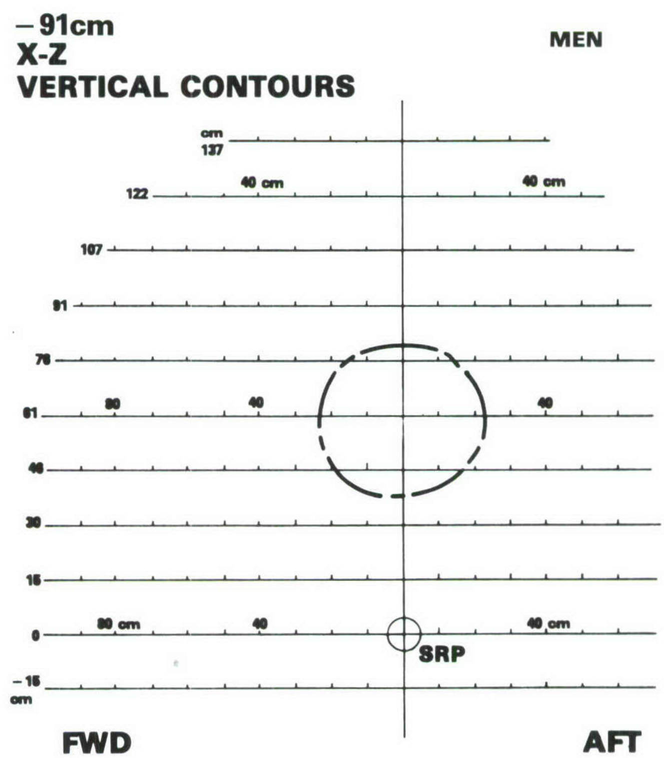


Figure 41. Vertical (X-Z) Planes Through the 5th, 50th, and 95th Percentile Reach Envelopes at −76 cm (Right) from SRP and through the 95th Percentile Reach Envelope at −91 cm (Right) from SRP — Men.

RESULTS

The principal results of this investigation of reach capability are presented in the form of tabular and graphic material. Data describing horizontal (X-Y), vertical (Y-Z), and vertical (X-Z) planes are presented beginning with table 2. Graphic presentations follow the tabular data. Attempts were made to produce as accurate a set of drawings as possible. Unfortunately, some small inaccuracies crept into them in the process of making presentable drawings from the original work sheets. Tabular data, which are not as susceptible to these problems, survived such manipulation unscathed. The diagrams are useful in visualizing the envelopes, but actual dimensional values should be taken from the tables.

TABLE 2

REACH CAPABILITY ENVELOPE
WOMEN, 5TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From SRP-V

Vector — Degrees from Forward*

Horizontal Plane	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm																								
(54 in)																								
+122 cm																								
(48 in)																								
+107 cm	13	11	9	8	8	8	9	10	11	14	17	19	23	25	29	30	33	36	36	30	23	19	17	14
(42 in)																								
+ 91 cm	23	20	18	18	18	20	21	25	29	33	36	41	44	47	49	53	53	57	54	46	32	28	26	25
(36 in)	7	7	7	6	6	7	8	8	9	10	11	11	11	10	9	8	8	7	6	6	7	7	7	7
+ 76 cm	18	16	17	18	17	22	25	33	38	43	46	51	55	58	59	62	64	65	66	41	32	28	27	24
(30 in)	13	13	11	9	7	7	7	8	8	9	10	12	10	9	8	8	7	7	7	9	11	13	13	13
+ 61 cm					20	25	29	36	43	48	52	56	60	63	67	68	69	70	69	33	27	23	21	17
(24 in)					15	15	13	10	8	8	8	7	8	8	8	10	13	15	15	15	13	10	10	10
+ 46 cm						26	30	36	43	48	51	57	62	65	68	70	70	71	70					
(18 in)						15	16	17	17	17	15	13	15	17	17	17	27	41	32					
+ 30 cm								31	37	42	48	55	58	61	65	67	68	69	67					
(12 in)								14	17	17	16	17	16	17	17	17	28	43	35					
+ 15 cm														53	55	59	60	60	59	56	53			
(6 in)														36	28	23	20	17	28	38	33			
0 cm															36	39	41	43	41	39	33	23		
(SRP)																								
− 15 cm																								
(−6 in)																								

*Axis is Seat Reference Point — Verticle (SRP-V).

TABLE 3

REACH CAPABILITY ENVELOPE
WOMEN, 50TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From SRP-V

Vector — Degrees from Forward*

Horizontal Plane	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm																								
(54 in)																								
+122 cm																								
(48 in)																								
+107 cm	25	23	22	20	20	20	22	24	27	29	32	36	38	43	44	48	51	51	52	46	39	36	31	29
(42 in)																								
+ 91 cm	33	29	26	25	27	29	33	36	39	44	48	52	55	57	61	63	65	67	67	63	48	44	41	39
(36 in)	7	7	7	6	6	7	8	8	9	10	11	11	11	10	9	8	8	7	6	6	7	7	7	7
+ 76 cm	32	30	22	27	30	33	39	44	48	52	56	58	62	65	70	70	72	73	74	67	49	41	39	38
(30 in)	13	13	11	9	7	7	7	8	8	9	12	10	9	8	8	7	7	7	7	9	11	13	13	13
+ 61 cm	23	23	27	25	31	35	41	47	51	55	60	63	67	70	73	74	76	77	77	72	36	30	28	28
(24 in)	10	10	13	15	15	15	13	10	8	8	8	7	8	8	8	10	13	15	15	15	13	10	10	10
+ 46 cm					28	33	38	45	50	55	58	63	67	70	73	75	76	76	77	73				
(18 in)					16	15	16	17	17	17	15	13	15	17	17	17	18	23	24	42				
+ 30 cm						28	33	38	45	51	55	60	63	66	69	72	72	72	72	69	65	48		
(12 in)						13	13	14	17	17	16	17	16	17	17	14	13	20	24	32	41	38		
+ 15 cm													57	58	60	63	63	64	63	61	58	51	41	
(6 in)													53	36	36	28	23	20	17			27	37	
0 cm															44	48	48	50	48	46	42	33	25	
(SRP)																								
− 15 cm																								
(−6 in)																								

*Axis is SRP-V.

TABLE 4

REACH CAPABILITY ENVELOPE
WOMEN, 95TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From SRP-V

Horizontal Plane	Vector — Degrees from Forward*																						
	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm																								
(54 in)																								
+122 cm	25	21	18	17	17	17	18	20	22	22	22	23	23	25	28	29	32	37	40	42	38	32	29	27
(48 in)																								
+107 cm	43	38	35	33	31	33	37	38	40	43	45	46	48	52	56	57	60	61	61	60	54	50	48	48
(42 in)																								
+ 91 cm	50	45	41	39	39	40	43	46	50	55	58	61	63	64	69	70	71	73	73	70	65	59	56	54
(36 in)	7	7	7	6	6	7	8	8	9	10	11	11	11	10	9	8	8	7	6	6	7	7	7	7
+ 76 cm	49	42	39	43	46	44	51	53	56	62	64	69	72	74	76	77	77	79	79	75	70	60	56	51
(30 in)	13	13	11	9	7	7	7	8	8	9	10	12	10	9	8	8	7	7	7	9	11	13	13	13
+ 61 cm	38	41	36	43	48	45	53	55	60	63	66	71	74	76	79	81	81	81	82	79	69	56	46	41
(24 in)	10	10	13	15	15	15	13	10	8	8	8	7	8	8	8	10	13	15	15	15	13	10	10	10
+ 46 cm				36	39	44	50	53	58	62	66	70	75	77	79	81	81	81	82	79	72	38		
(18 in)				15	16	15	16	17	17	17	15	13	15	17	17	17	16	15	16					
+ 30 cm				32	36	39	44	51	55	58	62	66	72	75	76	78	79	79	79	75	72	63	57	
(12 in)				17	12	13	13	14	17	17	16	17	16	17	17	14	13	13	12					36
+ 15 cm					27	29	37	41	46	51			69	70	71	71	72	72	70	67	65	61	53	
(6 in)						17	20	23	28	36			53	36	28	23	20	17				25	31	
0 cm													57	55	57	58	60	60	58	53	52	48	40	
(SRP)																								
− 15 cm														37	39	39	39	39	40	32	29			
(−6 in)																								

*Axis is SRP-V

TABLE 5

REACH CAPABILITY ENVELOPE
MEN, 5TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From SRP-V

Horizontal Plane	Vector — Degrees from Forward*																							
	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm (54 in)																								
+122 cm (48 in)	11	11	10	10	10	9	10	11	13	15	17	20	23	28	30	30	32	33	34	33	25	15	11	10
+107 cm (42 in)	25	20	27	23	23	25	29	30	36	42	44	49	51	56	58	62	62	65	65	51	46	31	26	29
+ 91 cm	25	22	25	26	25	29	32	40	44	53	55	58	63	67	70	73	72	75	74	45	46	32	26	27
(36 in)	10	10	9	9	8	8	8	9	10	10	11	11	11	10	10	9	8	8	8	9	9	10	10	10
+ 76 cm	20	21	19	26	25	32	39	46	51	57	62	65	70	72	77	79	79	80	81	28	37	25	22	23
(30 in)	6	6	6	7	7	6	6	7	8	10	11	13	11	10	8	7	6	6	7	7	6	6	6	6
+ 61 cm						32	39	46	51	60	63	67	72	76	79	82	82	84	82					
(24 in)						27	24	20	16	15	12	11	12	14	16	20	24	53	50					
+ 46 cm						29	34	42	48	57	63	67	72	76	79	81	82	83	81					
(18 in)						18	18	18	17	17	17	17	17	17	17	38	48	43	64					
+ 30 cm								37	44	55	55	40	67	70	73	77	77	77	76	71				
(12 in)								20	20	21	20	20	20	21	20	29	34	33	47	66				
+ 15 cm														61	63	66	67	67	65	63	57			
(6 in)														43	30	24	19	15			21			
0 cm (SRP)														44	47	51	49	48	48	46	41			
− 15 cm (−6 in)																								

*Axis is SRP-V.

TABLE 6

REACH CAPABILITY ENVELOPE
MEN, 50TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From SRP-V

Vector — Degrees from Forward*

Horizontal Plane	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm (54 in)																								
+122 cm	29	27	25	25	25	25	27	28	30	33	36	39	44	49	51	52	53	55	56	55	52	44	36	36
(48 in)																								
+107 cm	37	33	30	31	30	32	37	41	46	50	53	58	61	65	69	69	70	70	72	69	61	51	51	41
(42 in)																								
+ 91 cm	37	31	28	32	30	39	45	51	55	59	63	67	70	74	77	79	81	80	81	79	57	49	48	40
(36 in)	10	10	9	9	8	8	8	9	10	10	11	11	11	10	10	9	8	8	8	9	9	10	10	10
+ 76 cm	28	27	28	32	38	43	51	56	61	63	69	74	76	79	84	84	86	86	86	83	44	41	38	32
(30 in)	6	6	6	7	7	6	6	7	8	10	11	13	11	10	8	7	6	6	7	7	6	6	6	6
+ 61 cm	18			30	36	43	51	57	62	66	71	76	79	81	84	87	88	89	87	86	29	25	20	20
(24 in)	10			19	24	27	24	20	16	14	12	11	12	14	16	20	24	27	24	19	15	11	10	11
+ 46 cm					32	41	49	55	61	65	69	74	77	81	84	86	88	88	84	83				
(18 in)					18	18	18	18	17	17	17	17	17	17	17	18	18	18	41	58				
+ 30 cm						34	43	49	56	60	60	69	74	77	79	82	83	83	80	77	72	62		
(12 in)												60												
						17	18	20	20	21	20	40	20	21	20	20	21	23	23	30	37	57		
												20												
+ 15 cm						20	28	36	44	49	47		65	68	70	73	72	74	71	70	65	56	43	
(6 in)						15	19	24	30	43			60	43	30	24	19	15				29	36	
0 cm													50	53	56	60	57	57	56	53	49	40	29	
(SPR)													40	44	31	25	23	22	23	18	21	23	21	
+ 15 cm																32	32	27	20					
(−46 in)																18	16	15	16					

*Axis is SRP-V.

TABLE 7

REACH CAPABILITY ENVELOPE
MEN, 95TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From SRP-V

Vector — Degrees from Forward*

Horizontal Plane	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm (54 in)	27	26	25	25	25	25	26	27	28	29	32	33	37	37	38	39	40	40	38	36	36	34	32	29
+122 cm (48 in)	44	43	41	37	38	38	38	42	47	50	54	57	59	63	65	67	66	66	66	66	62	57	54	50
+107 cm (42 in)	53	51	49	43	46	47	48	53	59	61	66	69	71	75	77	80	80	79	79	79	74	70	63	58
+ 91 cm	55	56	51	46	50	51	54	60	65	68	74	76	80	83	86	88	88	88	88	87	82	72	63	60
(36 in)	10	10	9	9	8	8	8	9	10	10	11	11	11	10	10	9	8	8	8	9	9	10	10	10
+ 76 cm	53	51	41	45	48	55	58	63	69	72	77	81	86	88	90	92	93	93	93	91	88	57	58	54
(30 in)	6	6	6	7	7	6	6	7	8	10	11	13	11	10	8	7	6	6	7	7	6	6	6	6
+ 61 cm	32	32	33	43	46	55	59	65	69	74	79	83	88	90	93	93	94	95	94	92	88	42	37	36
(24 in)	10	11	15	19	24	27	24	20	16	14	12	11	12	14	16	20	24	27	24	19	15	11	10	11
+ 46 cm				34	43	52	56	62	66	77	81	86	88	91	91	93	93		92	89	86	74	36	
(18 in)				19	18	18	18	18	17	17	17	17	17	17	18	18	18	18	18	27	33	24	27	
+ 30 cm					36	47	51	57	62	67	72	78	83	84	86	88	88	89	88	84	82	77	65	
(12 in)												60												
					15	17	18	20	20	21	20	40	20	21	20	20	18	17	15	20	22	23	34	
												20												
+ 15 cm						38	41	48	53	58	62		76	77	78	81	79	81	79	78	74	70	61	53
(6 in)						15	19	24	30	43	60		60	43	30	24	19	15					32	32
0 cm (SRP)													62	63	66	69	67	67	67	66	61	55	48	41
− 15 cm (−6 in)														47	47	48	48	46	44	44	36	30		

*Axis is SRP-V

TABLE 8

REACH CAPABILITY ENVELOPE
WOMEN, 5TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=3
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes*																					
	−61 cm (24 in)		+46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)																						
+122 cm (48 in)																						
+107 cm (42 in)								25 3	8	36	5	27										
+ 91 cm (36 in)							14	51	7 20	57 7	22	51	16	41								
+ 76 cm (30 in)							6	64	7 22	65 7	29	62	26	55	10	36						
+ 61 cm (24 in)								67 22	15 25	70 15	31	67	30	60	20	49						
+ 46 cm (18 in)								69 34	15 26	71 41	30	69	30	64	18	51						
+ 30 cm (12 in)								66 34		69 43	4 28	66 4	25	60	14	46						
+ 15 cm (6 in)						46 22		58 18		60 22		58 22		51 22		28 15						
0 cm (SRP)								37 15		43 22		37 22										
+ 15 cm (−6 in)																						

* +=Forward, −=Aft from SRP-V

TABLE 9

REACH CAPABILITY ENVELOPE
WOMEN, 50TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes*																					
	−61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+ 76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)																						
+122 cm (48 in)																						
+107 cm (42 in)						15 10	15	50	20	50	20	48	9	34								
+ 91 cm (36 in)					13	55	21	64	7 29	67 7	32	64	27	56	14	38						
+ 76 cm (30 in)					9	64	17	72	7 33	73 7	39	71	36	64	25	53						
+ 61 cm (24 in)						70 39		76 22	15 35	77 15	41	75	40	69	29	57	6	34				
+ 46 cm (18 in)						70 43		75 30	15 33	76 23	39	74	37	69	28	58	5	34				
+ 30 cm (12 in)				46 32		64 28		71 28	15 28	72 20	4 33	70 4	32	65	25	53		20 3				
+ 15 cm (6 in)						53 11		62 15		64 15		62 16		56 22		39 15						
0 cm (SRP)						25 25		46 15		50 22		46 22		33 22								
− 15 cm (−6 in)																						

* +=Forward, −= Aft from SRP-V

TABLE 10

REACH CAPABILITY ENVELOPE
WOMEN, 95TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes* −61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)																						
+122 cm (48 in)							12	38	17	37	15	25										
+107 cm (42 in)			4	18	21	51	29	60	33	61	33	58	28	48	5	23						
+ 91 cm (36 in)			15	46	29	64	36	70	7 40	73 7	43	70	36	64	29	51		15 3				
+ 76 cm (30 in)			30	56	25	71	43	77	7 45	79 7	50	76	44	71	37	62	20	41				
+ 61 cm (24 in)				60 17	23	75	22 46	81 22	15 45	81 15	51	79	48	76	40	66	22	47				
+ 46 cm (18 in)				62 34		76 15	20 34	81 21	44 15	81 15	48	80	46	76	39	66	22	48				
+30 cm (12 in)				58 6		70 11	22 29	77 18	13 39	79 13	4 44	77 4	43	72	34	62	15	44				
+ 15 cm (6 in)				46 7		60 8		69 15	15 11	72 22	22 36	71 22	22 33	65 22	17 19	55 15		34 10				
0 cm (SRP)						46 5		57 15		60 22		58 22		50 22		31 15						
+ 15 cm (−6 in)								33 15		39 15		36 15		22 15								

* +=Forward, −=Aft from SRP-V

TABLE 11

REACH CAPABILITY ENVELOPE
MEN, 5TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes*																					
	−61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+ 61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)																						
+122 cm (48 in)								30	9	33	4	26										
								13														
+107 cm (42 in)						37	20	64	25	65	27	61	24	55	7	34						
						21																
+ 91 cm (36 in)						36	21	73	8	75	34	72	32	66	28	55						
						19			29	8												
+ 76 cm (30 in)							9	79	6	80	39	78	38	72	32	64	14	41				
							11	34	32	6												
+ 61 cm (24 in)								83	27	84	39	81	38	76	34	67	18	50				
								48	32	53												
+ 46 cm (18 in)								81	19	83	8	81	33	76	30	67	15	48				
								60	29	43	35	8										
+ 30 cm (12 in)						66		75		77	13	76	32	70	11	59						
						55		48		33	32	13			27	11						
+ 15 cm (6 in)						57		64		67		65		59		44						
						22		15		22		22		22		8						
0 cm (SRP)								45		48		48		39								
								15		22		22		22								
− 15 cm (−6 in)																						

* +=Forward, −=Aft from SRP-V

TABLE 12

REACH CAPABILITY ENVELOPE
MEN, 50TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes* −61 cm (24 in) LT	RT	−46 cm (18 in) LT	RT	−30 cm (12 in) LT	RT	−15 cm (6 in) LT	RT	0 cm (0 in) LT	RT	+15 cm (6 in) LT	RT	+30 cm (12 in) LT	RT	+46 cm (18 in) LT	RT	+61 cm (24 in) LT	RT	+76 cm (30 in) LT	RT	+91 cm (36 in) LT	RT
+137 cm (54 in)																				
+122 cm (48 in)					6	44	20	54	25	55	24	51	15	42						
+107 cm (42 in)				23 4	15	65	28	70	32	70	36	69	33	62	22	51				
+ 91 cm (36 in)				18 9	14	76	28	80	8 39	80 8	44	79	42	74	34	65	17	46		
+ 76 cm (30 in)					1	80	30	84	6 43	86 6	50	85	48	81	41	71	27	57		
+ 61 cm (24 in)				66 58		82 21	22	88 22	27 43	89 27	50	88	49	83	43	74	29	58	0	20
+ 46 cm (18 in)				68 54		79 51		85 43	18 41	88 18	8 48	86 8	47	82	42	72	27	57		
+ 30 cm (12 in)				61 29		72 27		80 27	19 34	83 23	13 43	81 13	42	76	11 36	67 11	11	50		
+ 15 cm (6 in)				47 20		64 13		70 15		74 22	22 30	71 22	22 32	66 22		55 5		28 11		
0 cm (SRP)						42 11		54 15		57 22		56 22		51 22		28 15				
−15 cm (−6 in)										15										

* +=Forward, −=Aft from SRP-V

TABLE 13

REACH CAPABILITY ENVELOPE
MEN, 95TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes*																					
	−61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)						15	20	34	25	40	23	37	5	17								
						7																
+122 cm (48 in)			6	41	28	59	34	64	38	67	37	65	34	60	23	45						
+107 cm (42 in)		34	23	62	36	74	43	77	47	79	46	79	46	74	38	64	22	46				
		11																				
+ 91 cm (36 in)		50	30	75	37	83	48	86	8	88	53	87	52	83	47	75	32	62	0	27		
		7							52	8												
+ 76 cm (30 in)		64	23	79	28	88	44	91	6	93	57	91	56	88	51	80	38	67	18	43		
		46							55	6												
+ 61 cm (24 in)		66		81	8	89	22	93	27	95	57	93	57	89	50	81	41	69	20	48		
		45		34			43	22	55	27												
+ 46 cm (18 in)		62		77		86	27	91	18	93	8	92	53	88	48	79	38	67	16	43		
		32		17		8	33	23	52	18	54	8										
+ 30 cm (12 in)		53		70		81		87	17	89	13	87	49	83	11	74	32	61	7	34		
		15		8		10		15	47	17	51	13			43	11						
+ 15 cm (6 in)		30	4	62		73		79	22	81	22	79	22	74	18	65		48				
		28				9		15	38	22	41	22	41	22	33	3		11				
0 cm (SRP)				37	4	59		65		67		65		61		48						
				11				15		22		22		22		15						
− 15 cm (−6 in)								42		46		47		36								
								15		15		15		15								

* +=Forward, −=Aft from SRP-V

TABLE 14

REACH CAPABILITY ENVELOPE
WOMEN, 5TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Frontal Plane
Through SRP-V

Horizontal Plane	Fore/Aft Planes* +61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		+76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)																						
+107 cm (42 in)									19	14	22	17	11	13								
+ 91 cm (36 in)							30	11	41 11	7 25	43	24	37	23	26	20						
+ 76 cm (30 in)							43	10	51 12	13 24	53	24	48	21	39	22	18	21				
+ 61 cm (24 in)					30 13		49 0		56 7		58 0	18 20	55	17	48	20	30	23				
+ 46 cm (18 in)					30 13		48 3		57 17		60 7		57 6		50	22	35	25				
+ 30 cm (12 in)							44 9		55 17		57 9		53 8		46	23	29	21				
+ 15 cm (6 in)											49 46		44	11 20 37	35	31						
0 cm (SRP)													23	22								
− 15 cm (−6 in)																						

* +=Left, −=Right from SRP-V

TABLE 15

REACH CAPABILITY ENVELOPE
WOMEN, 50TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Frontal Plane
Through SRP-V

Horizontal Plane	Fore/Aft Planes* +61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		−76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)																						
+107 cm (42 in)							25	15	36	29	39	30	32	27	20	20						
+ 91 cm (36 in)					20		44	25	52	7	53	39	48	36	41	35	23	22				
					3				11	39												
+ 76 cm (30 in)					41	6	53	26	58	13	60	37	57	35	51	36	34	32				
									12	38												
+ 61 cm (24 in)					44	8	57	18	64	18	65	18	62	26	55	36	42	37	7	13		
								20	7	28	0	27										
+ 46 cm (18 in)					43	3	56		63		65		62	15	55	33	42	38	3	8		
							3		17		5											
+ 30 cm (12 in)					37		53	0	60		62		58	22	51	46	37	34				
					4				17		3			28								
														45								
+ 15 cm (6 in)											55	10	51	45	41	38	18	18				
											46	43										
0 cm (SRP)												10	32	30	15	15						
												28										
− 15 cm (−6 in)																						

* +=Left, −=Right from SRP-V

TABLE 16

REACH CAPABILITY ENVELOPE
WOMEN,
95TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Frontal Plane
Through SRP-V

	Fore/Aft Planes*																					
Horizontal Plane	+61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		−76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)							15	8	23	27	22	28	10	26								
+107 cm (42 in)					27	10	42	37	46	48	46	46	44	42	33	34		18				
+ 91 cm (36 in)					44	27	55	46	61 11	7 54	61	54	58	51	50	46	36	33				
+ 76 cm (30 in)			29 5		54	25	63	45	69 12	13 51	70	54	66	52	58	51	46	41	14	21		
+ 61 cm (24 in)			32	15	55	24	65 0	18 37	71 7	18 41	72 0	18 45	69	49	62	49	51	45	28	29		
+ 46 cm (18 in)			29 3		54	18	65 3		70 17		73 3	18 30	70	43	62	51	51	46	29	29		
+ 30 cm (12 in)					48	15	61	9	66 17		69	2 17 55	67	56	60	53	48	43	20	20		
+ 15 cm (6 in)					37 2						65 46	20 52	63	53	54	46	37	29				
0 cm (SRP)									46 41		55 38	10 40	46	41	35	30						
− 15 cm (−6 in)											33	20	25	16								

* + =Left, − =Right from SRP-V

TABLE 17

REACH CAPABILITY ENVELOPE
MEN, 5TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Frontal Plane
Through SRP-V

Horizontal Plane	Fore/Aft Planes* +61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		−76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)									20	10	24	17	10	15								
+107 cm (42 in)							40	19	49	29	49	27	47	33	39	26	15	20				
+ 91 cm (36 in)					27 5		53	17	58 22	10 17	61	28	58	34	52	20	39	28				
+ 76 cm (30 in)					48	1	60	13	65 13	6 23	67	5 12 23	64	14	60	22	49	29	20	23		
+ 61 cm (24 in)					52	3	62 11		68 12		70 11		68 3		64 4		52	28	30	25		
+ 46 cm (18 in)					45 4		61 10		67 17		70 10		69 19		62 13 8	3	51	17	29	24		
+ 30 cm (12 in)					35 12		53 13		40 20		65 13		62 9		56	13	44	36	14	11		
+ 15 cm (6 in)													53	37	44	38	28	23				
0 cm (SRP)												10 15	34	29	21	14						
− 15 cm (−6 in)																						

* + =Left, − =Right from SRP-V

TABLE 18

REACH CAPABILITY ENVELOPE
MEN, 50TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Frontal Plane
Through SRP-V

	Fore/Aft Planes*																					
Horizontal Plane	+61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		−76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)							30	22	39	36	43	36	41	39	25	29						
+107 cm (42 in)					37	5	51	30	58	41	59	49	57	43	50	43	32	34				
+ 91 cm (36 in)					51	7	61	29	67 11	10 40	67	46	66	41	61	41	50	42	25	28		
+ 76 cm (30 in)			37 4		57	15	68	22	74 13	6 32	74	37	71	32	67	35	58	44	38	36		
+ 61 cm (24 in)			41 4		60	14	70 11		76 12		77 11		74	26	69	37	58	46	42	41		
+ 46 cm (18 in)			36 8		58	9	68 10		74 17		75 10		72	5	67	18	57	48	40	35		
+ 30 cm (12 in)					52	2	58 13		69 60 40 20		71 13		70	53	64	53	52	46	30	23		
+ 15 cm (6 in)					33 14						63 58	10 44	60	49	53	46	39	35				
0 cm (SRP)									50 38	10 33	44	36	36	27								
− 15 cm (−6 in)																						

* + =Left, − =Right from SRP-V

TABLE 19

REACH CAPABILITY ENVELOPE
MEN, 95TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=30
Values in Centimeters
From Frontal Plane
Through SRP-V

Horizontal Plane	Fore/Aft Planes*																					
	+61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		−76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)							25	21	33	29	31	30	23	20								
+122 cm (48 in)					37	27	51	41	57	50	55	52	55	50	45	43	26	25				
+107 cm (42 in)			30	8	53	40	65	51	69	58	69	62	67	63	61	57	48	46	25	23		
+ 91 cm (36 in)			46	18	63	46	72	53	76 11	10 60	78	62	75	62	70	62	62	57	43	44		
+ 76 cm (30 in)			53	15	69	29	77	50	81 13	6 54	83	56	81	50	75	61	66	63	51	49	15	15
+ 61 cm (24 in)			54	11	70	23	79 11	18 29	83 12	18 36	85 11	18 36	83	42	77	62	69	64	53	51	23	23
+ 46 cm (18 in)			50	8	68	17	77 10		81 17		84 10	20 43	81	60	75	65	66	62	50	46	18	16
+ 30 cm (12 in)			39	2	62	10	72 13		78 60 40 20		80 13	11 62	77	67	71	65	61	56	43	38		
+ 15 cm (6 in)					49	6	61 58			32 53	74 58	10 59	70	61	63	57	50	47	23	23		
0 cm (SRP)										20 41	60 38	10 47	55	47	48	42	30	27				
− 15 cm (−6 in)											43	20	36	25	18	1						

* +=Left, −=Right from SRP-V

DISCUSSION

The most important anatomical factors influencing the size and shape of the grasping-reach envelope are the length of the arm and the characteristics of motion within the shoulder, at the elbow, and at the wrist. Variability in the lengths of the segments of the arm and mobility at the shoulder are responsible for the inconstant radii of the reach envelopes (see Dempster, 1955).

Because of the complexity of shoulder anatomy, it is difficult to distinguish a stationary center of rotation for more than a very limited range of arm movement. The center of rotation for any given movement is temporary and migrates as the shoulder performs. Dempster (ibid.) charted the centers of shoulder rotation for a series of arm positions and found that no point could be considered a joint center for more than about 10° of movement. The migration of the center of shoulder rotation makes it extremely difficult to determine the distance from the mean shoulder joint center to grasping reach at any arm position.

In any discussion concerning the mobility of the shoulder, references carrying the implication that the shoulder is composed of a single joint are misleading. The shoulder is comprised of three separate joints: (1) the glenohumeral, between the humerus and the scapula, (2) the acromioclavicular, between the lateral end of the clavicle (collar bone) and the acromial process of the scapula, and (3) the sternoclavicular, between the medial end of the clavicle and the manubrium of the sternum. Movement of the shoulder is the result of synchronous participation of these joints. In elevating the arm in the medial or lateral plane, for example, movement occurs at all three joints, the most obvious being at the glenohumeral joint.

Inman, Saunders, and Abbott (1944) report that during the first 30° of elevation of the arm in the frontal plane (vertical abduction) and the first 60° of elevation parallel to the medial plane (flexion), participation of the scapula is variable. Higher elevations, however, are invariably accompanied by simultaneous movements of the scapula. They found that when the scapula is fixed, the arm may be raised actively to the horizontal position and passively through an additional 30°. Further movement is obstructed mechanically by the greater tubercle of the humerus striking the acromial process of the scapula.

During these movements of the arm, the clavicle follows as a stabilizing strut and permits elevation of the scapula through rotation of its sternal and scapular joints. These investigators found that by manually preventing rotation of the clavicle around its long axis, the arm could be elevated in the median and frontal planes to just above shoulder level, through about 110°. Since the mean for arm flexion is 188° (Barter, Emanuel, and Truett, 1957), the result is a mean reduction in mobility of about 78°. Thus, when one of these joints is rendered inoperable, a significant reduction in mobility at the shoulder can result.

The method employed by Inman, Saunders, and Abbott to fix the scapula consisted of a harness resembling the shoulder harness and lap belt which, until recently, was found in most military and civilian aircraft. While in automobiles there was not the requirement to cinch-up the harness to immobilize the torso, in aircraft it was often necessary to do so for the purpose of protecting the pilot against violent buffetting and impact. When the harnesses were tightened, the scapulae were jammed against the seat back and the shoulders were held down. The range of free movement of the scapulae was severely reduced. Such restriction in shoulder mobility results directly in reduced reach capability.

Other characteristics that play a role in generating the reach envelopes are body dimensions. They include:

- the distance between the joint-center of the glenohumeral joint (often used as an approximation of the shoulder "joint") and the sitting surface, for which Acromial Height, Sitting, minus 3.5 cm* is a reasonable approximation,
- half the distance between the right and the left glenohumeral joint centers, approximately half Biacromial Diameter, and
- the lengths of the segments of the arm.

The value for Acromial Height, Sitting, minus 3.5 cm will closely approximate the height of the joint center of the glenohumeral joint when the arms are relaxed at the side. Since the shoulder invariably rises when the arm is brought to the forward or lateral horizontal positions, the levels at which the maximum forward and lateral reaches are attained can be expected to be somewhat higher than the center of rotation at the shoulder when the arm is down. To estimate this difference, Acromial Height was measured on 10 men in the conventional manner with the arm pendant, then with the right arm forward, and then out to the side. With the arm forward, Acromion rises approximately 3.2 cm; when in the lateral position, it rises about 5 cm. Thus, the center of rotation of the glenohumeral joint will rise by essentially the same amount. The mean level of this joint for men during forward horizontal reach, then, can be expected to be about 60.8 cm above SRP [mean Acromial Height, Sitting (61.1 cm) minus Dempster's estimate of the location of the glenohumeral joint center (3.5 cm) plus the average rise in the joint center when the arm is brought to the forward horizontal position (3.2 cm)]. The mean level of the glenohumeral joint during lateral reach can be expected to cluster at about 62.6 cm above SRP. Among women this joint would rise to about 55.2 cm with the arm forward and horizontal; for lateral reach, 57 cm.

The distance between the right and the left glenohumeral joint centers (for which Biacromial Diameter can be used as an estimate) has relatively little influence on the size and shape of the reach envelope. It does contribute to the lateral displacement from the median plane of the individual envelopes through a distance approximating half the variability for this dimension, or about 7.5 cm for men and 5.5 cm for women.** These and other features of shoulder mobility are responsible for the difficulty met when attempting to model these joints.

In determining the size and shape of the sector of the reach envelope between L30° and R120°, total arm length is, of course, very important. Variations in the lengths of the segments of the arms are relatively unimportant. Between the 30 cm and higher contours a gradual shortening of the radii of the arcs to the left of L30° and to the right of R120° are found. At points along the reach curves where the curve radii begin to shorten, the shoulder may be considered to have rotated maximally, and reach at angles beyond these points is gained through the mobility of the elbow ("around" the torso) and, to a minor extent, the wrist.

The potential mobility of the glenohumeral joint in the lower part of the Y-Z plane (vertical adduction) and the medial part of the X-Y plane (horizontal adduction) is considerably greater than demonstrated. In performing these movements, and those in between, the torso becomes a substantial obstruction. It follows that these movements will meet with greater resistance among individuals with larger torsos than among those who are smaller.

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*Dempster (1955) reports that the joint center for the glenohumeral joint is approximately 3.5 cm below Acromion.

**8.1 cm for a 50/50 mix of men and women.

The subject with great muscular development or heavy deposition of fat about the shoulders, chest and upper arms is likely to have less capability to adduct his arm than the subject with lesser amounts of these tissues. Although Fisk and Colwell (1944) stated that this was not true,* their investigation of joint mobility treated only one class of movements of the arm, namely rotation of the humerus about its longitudinal axis at selected elevations of the arm. In these rotatory movements of the humerus, there is virtually no interference between the tissues of the torso and the upper arm, hence a decrement in mobility due to such opposition would not be expected. In consideration of the possible opposition of body tissues to joint movement, this one class of movements is not representative of others of the upper arm, such as adduction and abduction.

Barter, Emanuel and Truett (1957) ranked the mean mobility values for twelve motions, including adduction of the arm, and related them to physique. They found that in all motions, the rotund group had the least mobility. In seven movements, there was a progressive increase in mobility from the rotund group through the muscular, median and thin groups. The rotund group had less mobility in these joints; the thin group had greater.

After an investigation of the movement of joints in relation to sex and constitution, Sinelnikoff and Grigorowitsch (1931) reported that the asthenic** type males had significantly greater mobility in their joints than did the muscular types. Also, "the movement of joints in male pyknic*** types is less than in male muscular types." They also found that in those instances in which the female had less capability than males, these could be "explained by reference to fat layers in this sex" (ibid., p. 24).

The correlation coefficient for Weight and Chest Depth is .757, and that for Weight and Waist Depth is .755 (Roebuck, Kroemer and Thomson, 1975). We can expect, then, an inverse relationship between joint capability (i.e., shoulder adduction) and certain anthropometric dimensions (i.e., torso depth). This means that the rotund and muscular subjects will likely approach the 5th percentile of medial angular arm reach. The thin subjects are likely to have greater mobility and, consequently, greater angular reach than the rotund and muscular subjects. The capability of the thin subject will approach the 95th percentile. A similar, but less pronounced, situation can be expected regarding certain other movements of the upper arm.

During forward reach in the horizontal plane, full forward flexion of the shoulder can increase reach capability by 10 to 15 cm. Elevation of the shoulder can account for a similar increase when reaching overhead. Understandably, given two subjects with the same arm length, the subject with greater shoulder mobility will find that he has greater forward reach than the one with less shoulder mobility. For similar reasons the subject with greater capability to abduct his arm will probably have greater angular reach capability around to the right rear. From joint-range data in Barter, Emanuel, and Truett (1957), it is possible to calculate the 5th and 95th percentile values for upper arm abduction, adduction, and other joint movements. For horizontal adduction of the right arm from the parasagittal plane through the shoulder, a value of 33° was obtained for the 5th percentile and 63° for the 95th percentile. The point on the envelope boundary where the radius begins to shorten will correspond to the end point of horizontal adduction of the arm. The 5th percentile for total horizontal abduction of the upper arm is 106° and 95th percentile is 162°. Although these data apply specifically to movements in the horizontal plane at shoulder level, similar obstruction to arm adduction can be expected when the arm is at angles above and below horizontal.

Because of the tendency for high values for certain body dimensions to reduce reach capability either by limiting the mobility of certain critical joints or by rendering some of the reach envelope inaccessible, the term "5th percentile reach envelope" cannot be considered descriptive of the reach capability of the ethereal "5th percentile man."

*"The development and the patient's physique had no bearing on . . . range of movement . . . at the shoulder. Coal heavers and sedentary office workers showed the same components in all movements" (p. 152).

**asthenic (slender)

***pyknic (rotund)

The lengths of the lower limbs play a role of some importance in influencing the reach envelope for the seated position. At the SRP and 15 cm levels, the subjects' knees protrude into their reach envelopes and restrict movements of the hand at these levels. The space above the knees becomes available at about 24 cm above SRP for women and at about 34 cm for men.

It is worthwhile to compare the reach data derived in this study with those obtained in others. Only one study has been performed in which comparable data have been produced: that being Kennedy (1964). Although the measuring apparatus were not identical, both employed a system of measuring rods originating from a point in space near the seated subject's shoulder. Both employed back switches to discourage lunging in the direction of reach, especially in the forward and left sectors. Techniques of data analysis were essentially the same for each study, although the 1964 study required one additional step.*

On comparing 5th, 50th, and 95th percentile horizontal contours at 76 cm (30 inches) above SRP, from the 1964 and the current studies, a few interesting differences come to light. See figure 42. The first and perhaps most obvious difference between the two sets of data is that the 1964 data described incomplete contours; whereas, in the current study, complete contours were developed. Ninety-five percent of the subjects of the current study could reach completely around themselves at this level. Since the complete contours may be considered "outside" boundaries, it is somewhat surprising that they were not uncovered in the 1964 study.

The percentile envelopes presented in the current study are slightly larger than those offered in 1964. The differences can be seen in table 20. Along vectors at the 76 cm (30-inch) level are comparable data from both studies, and small differences can be detected readily. The average difference between the radii of the 5th percentile envelopes from the two studies is 0.9 cm;** that for the 50th percentile envelope is 1.5 cm; for the 95th percentile envelope, 1.4 cm; those from the current study being larger. These rather small differences are likely to be insignificant. On examining the anthropometric characteristics of each study sample, it was found that, with regard to Functional Reach (see Appendix III), the present sample mean value is smaller by only 0.25 cm, hardly sufficient to produce such consistent differences. The only other explanation that can be advanced is that the differences in the release points of the two differently designed back-switches caused consistent, but small differences in reach.

Comparisons with other reach data available in the literature are difficult or inappropriate. Either the reference systems, such as in Chaffee (1969), Faulkner and Day (1970), and Stoudt (1973) are different from or unrelated to that used in the current study, or the geometry of the seat was different, such as in the studies referred to above and in Bullock and Steinberg (1973) and Bullock (1974). In Haslegrave (1970) and King, Morrow, and Vollmer (1947) as well as others, the manner of reach is different. To appreciate the very important decrement induced onto reach capability by flight clothing, it would be possible, after some manipulation of data and the reference system, to compare the data from the current study as well as that of Kennedy (1964) with those of Garrett, Alexander, and Matthews (1970) and Laubach and Alexander (1975).

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*It was necessary to "move" the origin of the radiating measuring rods from a point at shoulder level 10 inches to the right of the center of the seat to a point within the median plane of the seat, directly above SRP.

**Since the value at R120° from Kennedy (1964) is so divergent (54 X Average Deviation of all other values), it is considered suspect.

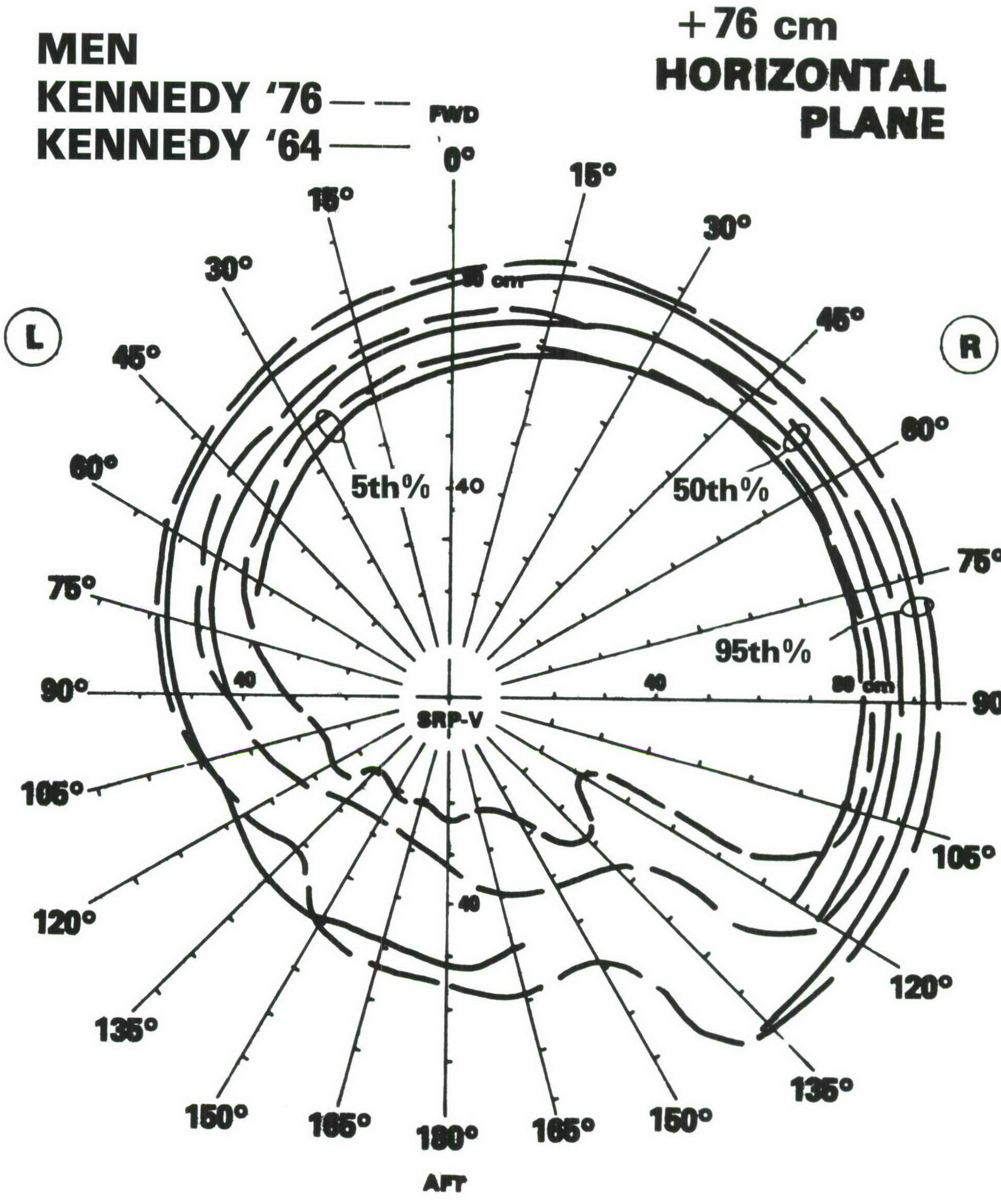

Figure 42. Horizontal Contours at 76 cm above SRP, 5th, 50th and 95th Percentile Reach Envelopes, Men — Comparative Data.

TABLE 20

COMPARATIVE REACH DATA — MEN*

Horizontal Plane at 76 cm above SRP												
Vector		5th *				50th *					95th *	
from SRP-V	'64			'76		'64		'76		'64		'76
L165°			20				28	48	53			
L150			21				27	49	51			
L135			19				28	51	41			
L120			26				32	48	45			
L105			25				38	48	48			
L90°			32	43	43	53	55					
L75			39	48	51	57	58					
L60	44	46	53	56	62	63						
L45	48	51	57	61	67	69						
L30	55	57	62	63	72	72						
L15	60	62	68	69	75	77						
0° (Fwd)	65	65	72	74	79	81						
R15	69	70	76	76	84	86						
R30	74	72	80	79	87	88						
R45	77	77	82	84	88	90						
R60	79	79	83	84	91	92						
R75	79	79	84	86	90	93						
R90°	79	80	84	86	91	93						
R105	79	81	84	86	90	93						
R120	77	28**	83	83	88	91						
R135			37				44	88	88			
R150			25				41			57		
R165			22				38	50	58			
180°(Aft)			23				32	51	54			
Average Deviation	−0.9	+0.9	−1.5	+1.5	−1.4	+1.4						

*Kennedy (1964) vs Kennedy (Current Study) — values in centimeters
**See footnote, page 75.

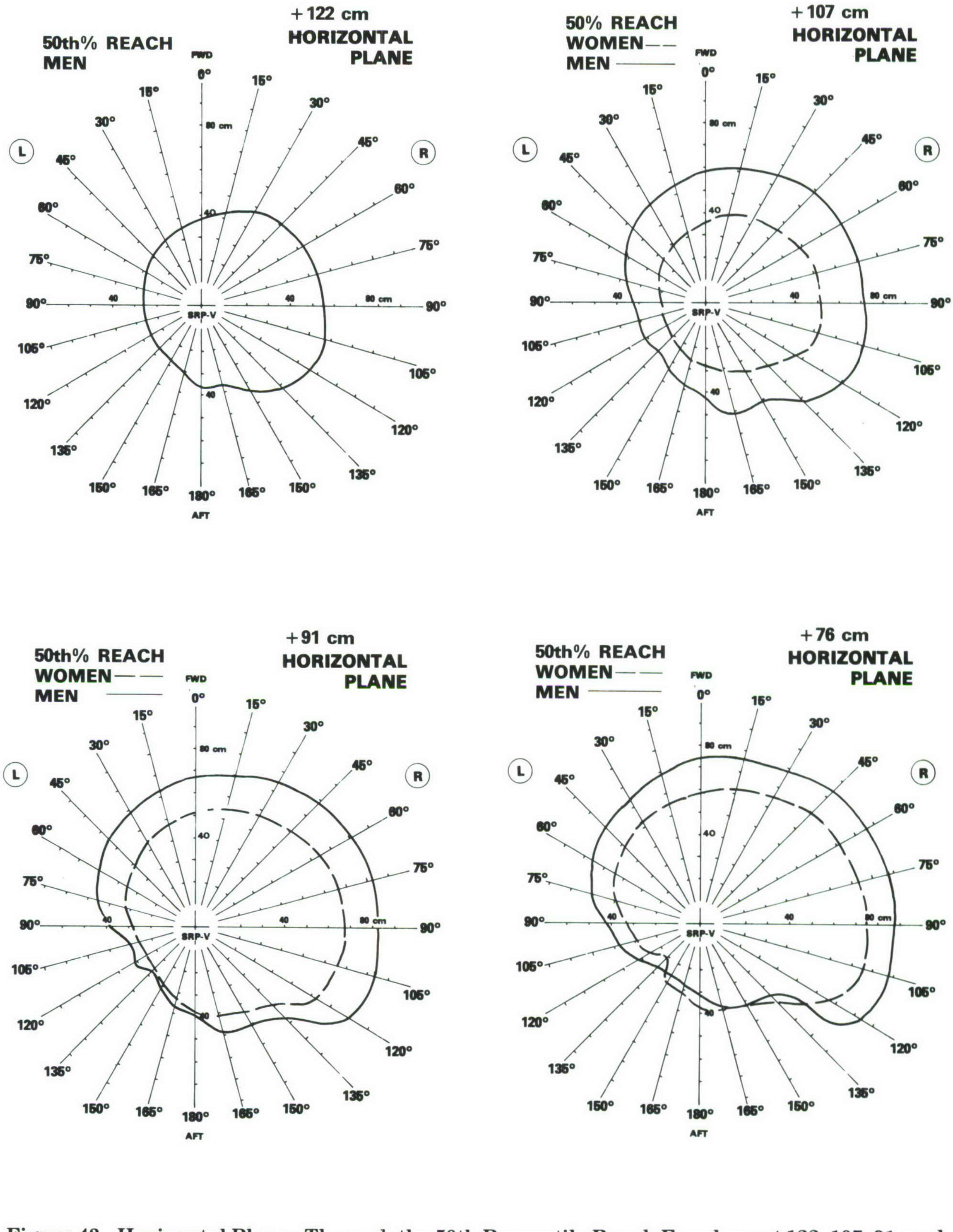

Figure 43. Horizontal Planes Through the 50th Percentile Reach Envelope at 122, 107, 91, and at 76 cm Above SRP — Men and Women.

The differences between the reach capability of women and men, as reported here, can be seen in the illustrations beginning with figure 43. These presentations consist of horizontal contours at intervals through the 5th percentile reach envelopes of men and women. The 50th percentile envelope was selected, since, of all such percentile envelopes, it best represents the population.* The 50th percentile reach envelope for men reaches to 133 cm above SRP (72 cm above the center of the measuring plane); that of the women, to 118 cm (57 cm above the center of the measuring plane). Therefore, in the first contour, at 122 cm above SRP, figure 43, the women are not represented.

As expected, the 50th percentile envelope of the women is smaller in its radii from SRP-V. Beginning with the +61 cm level and downward through the +30 cm level, we see evidences of greater capability for the women in terms of angular reach to the rear. We can surmise that this is due primarily to generally greater mobility in the shoulders found among women.

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*In an anatomical sense, the horizontal contours for men and women presented here, are not comparable. To be so, the initial contour would have to be at the average center of joint rotation at the shoulder for each, the men and women. Other contours would have to be taken at proportional intervals above and below this initial contour. This interval, rather than being the same for each, would need to be a fraction of the distance to the highest contour, which would be tangent to the top of the envelope. Other contours, established in similar fashion, would need to be established below the initial contour at shoulder level. However, for application to workstations, which is the main concern of this research, the various contours are comparable, since their distances from SRP are identical.

APPLICATION

The anthropometric percentile provides a useful tool to designers of work stations and equipment. The percentile is readily understood and applied. Percentiles provide a scale whereby the relative value of a dimension can be recognized immediately. For instance, when the 5th percentile is specified for a dimension, it is immediately known that it is a relatively small value, considering the range of values for that dimension; that exactly 5 percent of the total number of values are smaller and 95 percent are larger. When considering the 95th percentile for a given dimension, we know that it is a relatively large value, that 95 percent of the population of values are smaller in this dimension and 5 percent are larger. These simple properties make the percentile important in specifying the size of any space within which men and women are to work, or of any equipment to be handled or worn. When used in an appropriate manner, accommodation for a large segment or most of the using population can be assured.

In many operating compartments and work stations it is impractical to attempt to accommodate the entire range of body sizes found in the population, to say nothing of the variety of other human attributes and limitations. For that matter, the limits of many such variables within a population are often unknown. There is always a small percent of the general population who, for one reason or another, cannot function in the workspace. If sizable numbers of possible users are unable to function in the workspace and yet do not display characteristics inherently incompatible with the operation, then the designer has exercised excessive restrictions.

The policy in the military services as well as in the private sector has been to design equipment and vehicle operating stations such that the central 90 to 95 percent will be specifically accommodated in terms of body size. Generally, the 5th and 95th percentiles in important body dimensions are selected as limits. Since many of those below the 5th and above the 95th percentiles accommodate themselves to the design, only a small percentage has difficulty performing adequately.

There are many situations in which it is highly undesirable to force otherwise qualified users to attempt to accommodate themselves to the design. For instance, in specifying the distance from SRP to the forward edge of the seat, the length should be such that the users will not experience pressure in the popliteal and calf regions of the legs. Long-term pressure in these areas has been suspected among Air Force flight surgeons to cause phlebitis. To prevent this, it is necessary to use a small value (often the 1st percentile for Buttock-Popliteal Length* to establish this dimension. Use of this value can assure that essentially none of the population will feel the discomfort of a seat that is too long for the thighs.

Not all such critical dimensions are taken from the lower percentiles. In fighter-type aircraft, the primary means of emergency escape is an ejection seat. In an emergency, either on the ground or in flight, the pilot often must eject from the aircraft as rapidly as possible, frequently in less than a second. The only way that this can be accomplished is to be literally "shot" out of the cockpit via his ejection seat. Obviously there should not be any unyielding obstructions to his passage. One critical dimension is his fore-and-aft clearance. This is determined by the extent that his knees protrude from the seat. The critical body dimension is Buttock-Knee Length (see Appendix III). The clearance distance must accommodate all the using population, for if it does not, a dangerous situation is created for those pilots whose thigh length is in the upper percentiles. Therefore, the value very near the top of the range for this dimension should be accommodated. In practice, however, engineering considerations often dictate the space available for ejection clearance. Such a restriction effectively defines the anthropometric upper limit of the using population.

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*Buttock-Popliteal Length: The subject sits erect, his feet resting on a surface so that the knees are flexed at right angles. Buttock-Popliteal Length is the distance from the rearmost point of the right buttock to the popliteal region within the angle formed beneath the knee, along a line parallel to the axis of the thigh.

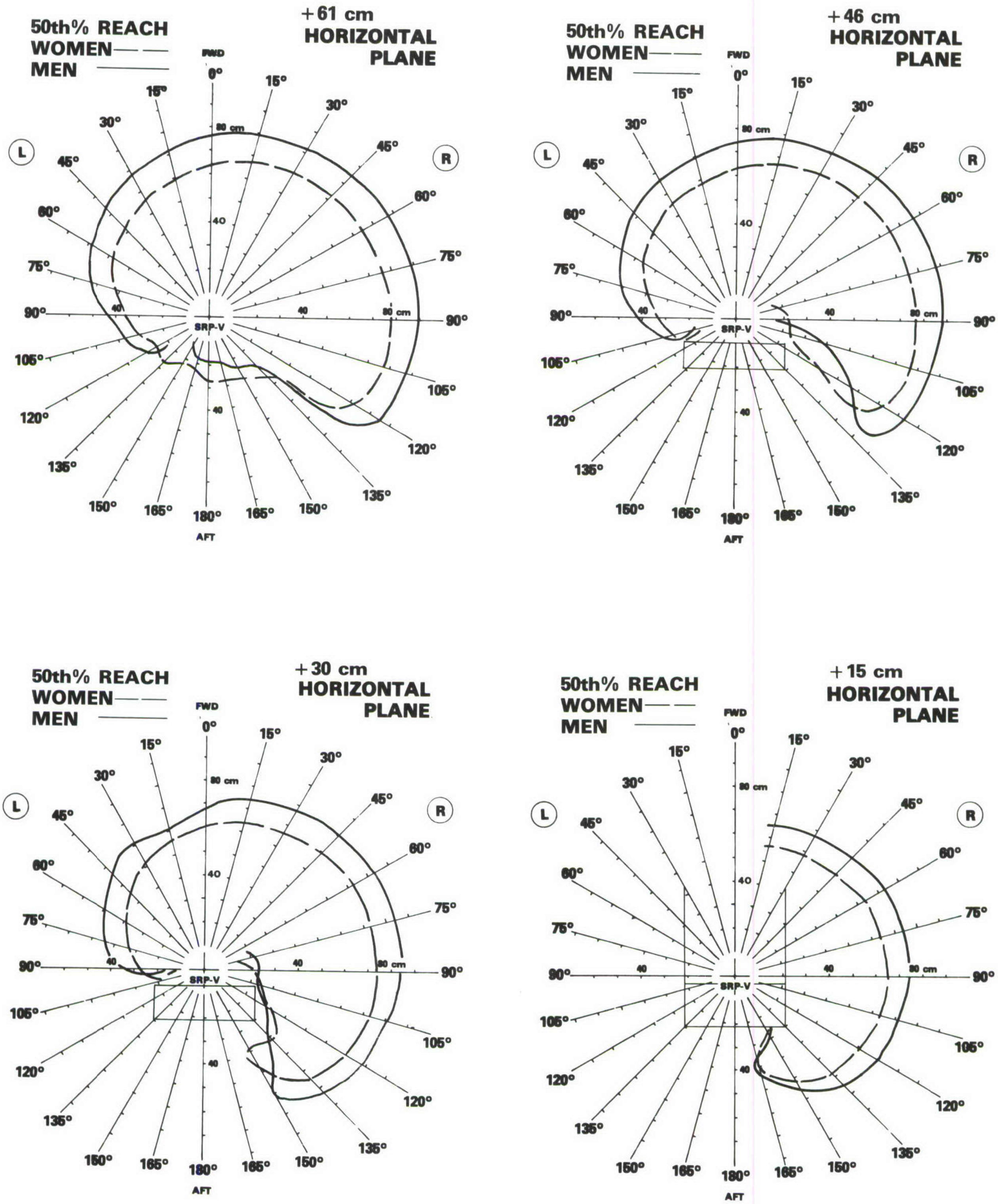


Figure 44. Horizontal Planes Through the 50th Percentile Reach Envelopes at 61, 46, 30, and at 15 cm Above SRP — Men and Women.

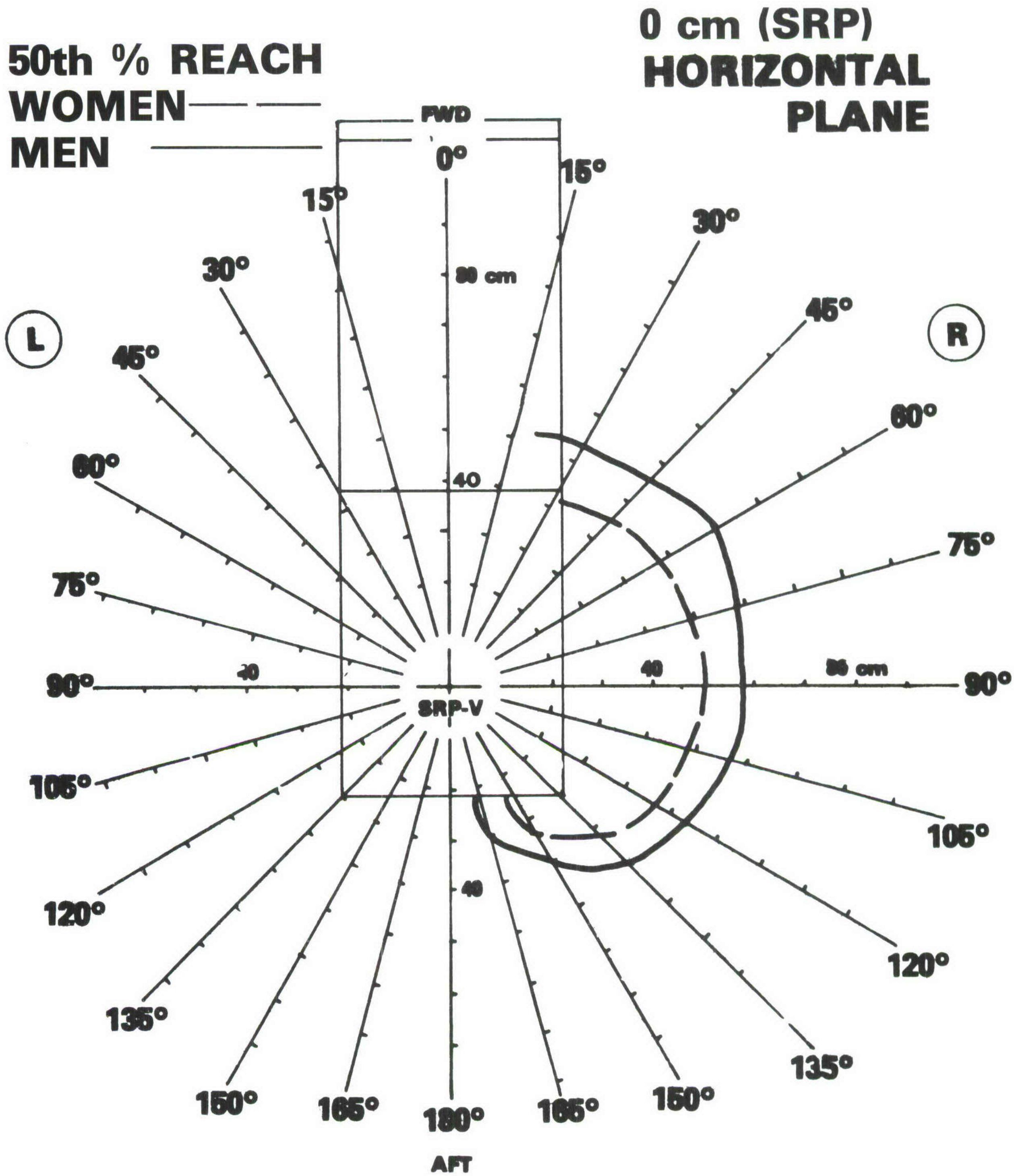
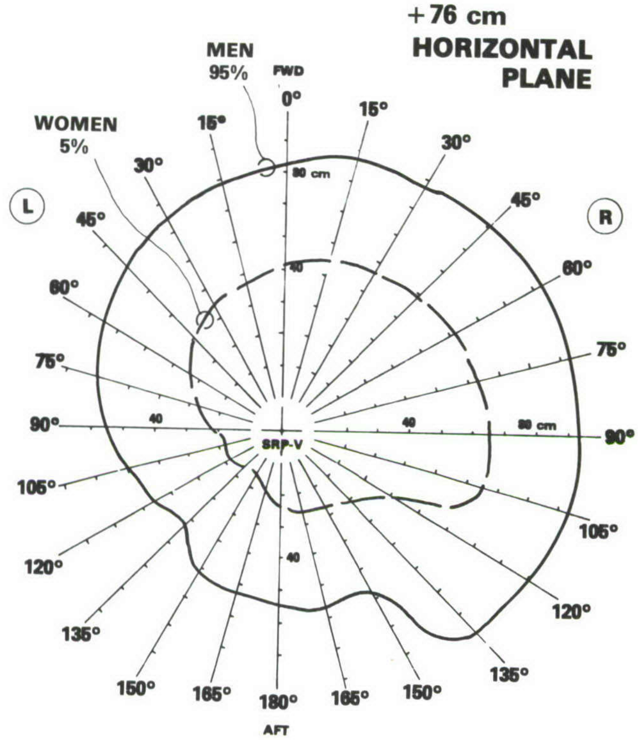


Figure 45. Horizontal Planes Through the 50th Percentile Reach Envelopes at SRP Level — Men and Women.



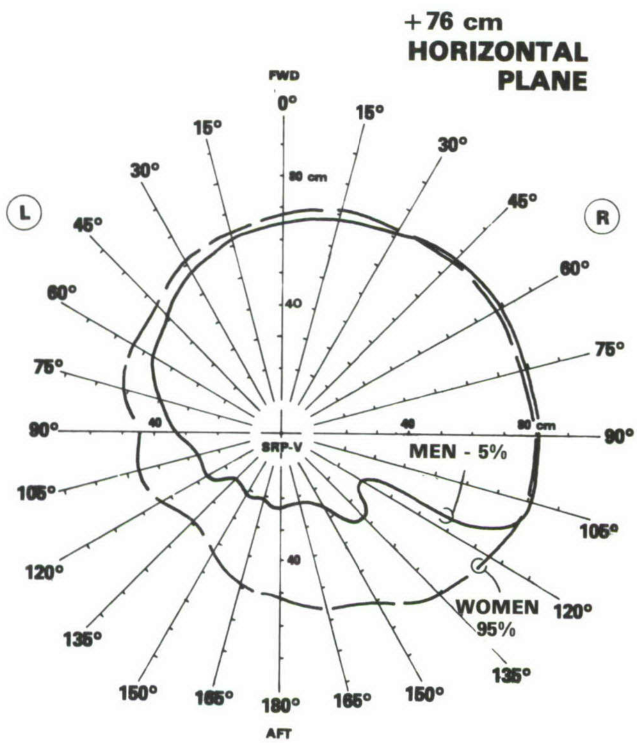


Figure 46. Horizontal Planes Through the 5th Percentile (Women) and 95th Percentile (Men) Reach Envelopes and Through the 5th Percentile (Men) and 95th Percentile (Women) Reach Envelopes — at 76 cm Above SRP.

There are types of hand-operated controllers that, because of their importance, should be more convenient to reach than others. Their distance from the operator should be no greater than full arm reach with the elbow extended. He should not have to extend his shoulder or break contact between his back and the seat back in the act of reaching. In aircraft, these controllers include the control column, throttle, landing gear control, radio frequency selector, emergency power switch, external stores drop control, wing angle deployment, fire extinguisher switch, and other safety-of-flight functions. In automobiles they include the headlight switch, windshield wipers, ignition, radio controls, cigarette lighter, and vent controls. While all the automotive controls may not be primary, their location should be such that the operator does not have to disturb his position or take his eyes off the road to find and operate them. While we are strongly advised against lighting a cigarette while driving an automobile, how many accidents are caused by the driver who is drawn out of acceptable operating position while fumbling for the cigarette lighter — or by the driver who, in a sudden rainstorm, takes his eyes off the road to find the windshield wiper control? These are the kinds of controllers that are specifically of concern in this study. Others can be located by applying a lunging factor appropriate to the workstation under consideration.

In prescribing the placement of critical hand-operated controllers, particular attention should be given to those prospective operators with less reach capability. A control placed just inside his reach capability envelope will, of course, be within reach of those with greater reach. In this study, the 5th percentile reach envelopes for men and for women are offered to serve this purpose. Tabular data describing the 5th percentile envelope for a 50/50 mixed male-female population is presented in Appendix II.

If a controller must be grasped between the thumb and side of the second segment of the forefinger or with a forefinger and index finger made into a hook, the dimensions of the 5th percentile envelopes may be used as they are offered. Push-button controls may be positioned up to 7 cm* beyond the 5th percentile envelope. Controls that are gripped with the hand should not be placed beyond the 5th percentile envelope, *less* 5.5 cm.**

In the above, values for Arm Reach from Wall, Functional Reach, and Forearm Hand Length were taken from Hertzberg, Daniels, and Churchill (1954). The value for Elbow Grip Length was taken from Grunhofer and Kroh (1975). Since the actual distance measured in this study terminated 0.5 inch (1.27 cm) short of the tip of the thumb, this amount is subtracted from Functional Reach in the above calculation. See figure 22. See also the descriptions of Functional Reach and other dimensions in Appendix III.

The 50th and 95th percentile reach envelopes were derived primarily to provide an appreciation for the range of variability of reach capability not only within one sex, but across the sexes. Appreciation for the intrasex variability can be obtained by studying the graphic and tabular data describing their respective envelopes. A comparison between horizontal contours through the 5th percentile envelope at 76 cm above SRP for the women and 95th percentile envelope for the men (figure 46) helps in appreciating the range of variability between the sexes. The mean difference in the lengths of the radii for the two extreme envelopes is 32.13 cm, with the average deviation from the mean being 3.89 cm. If we ignore the rather sudden increase in the difference between these two envelopes at R120° and R135°, the mean difference would be 30.22 cm with an average deviation from the mean of only 1.70 cm. The illustration in figure 46 showing contours at the same level for the 95th percentile and 5th percentile envelopes for the women and men, respectively, is also informative. There is little difference between these two contours except to the extreme left and rear, where the reach capability of the women is greater.

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*$\overline{X}$ Arm Reach from Wall (87.86 cm) — [$\overline{X}$ Functional Reach (82.12 cm) — 0.5 in (1.27 cm)] = 7.01 (7) cm.
**$\overline{X}$ Forearm Hand Length (47.88 cm) — $\overline{X}$ Elbow Grip Length (35.20 cm) — 7.01 cm = 5.67 (5.5) cm.

In applying any anthropometric data, the designer must be fully aware of the conditions under which they were derived. Heretofore, investigators of arm reach have used lap belts and shoulder harnesses that were pulled taut to maintain the subject's position in the seat, or they were permitted relatively unrestrained torso movement. The reduction in shoulder mobility, and therefore reach capability, using a tight shoulder harness has been previously noted. Since any reduction in shoulder mobility causes a reduction in reach capability, the data so taken with tightly adjusted shoulder harnesses tend to be conservative. Although Morant and Ruffel Smith (1947) rightly insisted that controls must be operable from the restrained position, the extent of restraint has, since their writing, been considerably reduced. The shoulder harness and inertia reel used by some investigators allow more flexibility of movement in the shoulders and, consequently, greater reach capability than that advisable to guide the location of critical controls.

APPENDIX I

COMPARATIVE TABULAR DATA — ORIGINAL AND FINAL 5TH PERCENTILE — MEN AND WOMEN

The following tables compare 5th percentile original, unsmoothed reach data with final, smoothed data. Dimensions are presented that describe the horizontal (X-Y) plane at 61 cm above SRP, the vertical (X-Z) plane (at 0°-180°), and the vertical (Y-Z) plane (at L90°-R90°). The average differences are also reported for those vectors along which both original and final data are found. The 5th percentile envelopes were selected for comparison because of their importance in workstation layout and because, being extracted from the ends of the distributions of values, they would tend to be subjected to the greatest amount of smoothing. The average differences show that not a great deal of smoothing was necessary.

TABLE 21

HORIZONTAL (X-Y) PLANE AT 61 CM ABOVE SRP — IN CENTIMETERS
COMPARATIVE DATA — ORIGINAL AND FINAL
5TH PERCENTILE — MEN AND WOMEN

	L 165°	150	135	120	105	90	75	60	45	30	15	Fwd 0°	15	30	45	60	75	90	105	120	135	150	R 165	Aft 180°	Average Difference
Men Orig						32	39	46	51	60	64	64	72	76	79	83	82	84	82	27					+0.07
Men Final						32	39	46	51	60	63	67	72	76	79	82	82	84	82						−0.07
Women Orig					20	25	29	36	43	50	52	57	60	64	67	68	69	70	69	33	27	23	21	18	+0.25
Women Final					20	25	29	36	43	48	52	56	60	63	67	68	69	70	69	33	27	23	21	17	−0.25

TABLE 22

VERTICAL (X-Z) PLANE AT 0°-180° — IN CENTIMETERS
COMPARATIVE DATA — ORIGINAL AND FINAL
5TH PERCENTILE — MEN AND WOMEN

	Men				Women			
	0° Fwd		180° Aft		0° Fwd		180° Aft	
	Orig	Final	Orig	Final	Orig	Final	Orig	Final
+90°	63	63	63	63	49	49	49	49
+75°	64	64	62	61	49	49	50	48
+60°	65	65	56	56	50	51	43	44
+45°	67	67	37	37	52	52	37	36
+30°	66	66	25	25	51	51	27	27
+15°	65	67			53	53	20	20
0°	64	67			57	56	18	17
−15°	67	69			60	60		13
−30°	67	69			62	62		
−45°	48	46			53	65		
−60°	46				51	47		
Average Difference	−0.70	+0.70	+0.20	−0.20	−0.73	+0.73	+0.29	−0.29

TABLE 23

VERTICAL (Y-Z(PLANE AT L90°-R90° — IN CENTIMETERS
COMPARATIVE DATA — ORIGINAL AND FINAL
5TH PERCENTILE — MEN AND WOMEN

	Men				Women			
	L90°		R90°		L90°		R90°	
	Orig	Final	Orig	Final	Orig	Final	Orig	Final
+90°	63	63	63	63	49	49	49	49
+75°	58	62	65	66	44	44	51	51
+60°	49	51	74	70	38	37	57	57
+45°	42	42	77	77	30	30	59	60
+30°	37	37	80	80	26	26	64	64
+15°	34	34	81	81	26	25	67	67
0°	32	32	84	84	25	25	70	70
−15°	30	31	83	84	27	27	74	74
−30°	32	33	81	82	30	30	76	76
−45°	28	30	79	79	22	34	75	75
−60°			77	77		34	74	74
Average Difference	−1.00	+1.00	+0.09	−0.09	−1.00	+1.00	−0.09	+0.09

APPENDIX II

REACH ENVELOPES, 50/50 MEN AND WOMEN, 5TH, 50TH, AND 95TH PERCENTILE TABULAR DATA

— HORIZONTAL PLANES
— VERTICAL Y-Z PLANES
— VERTICAL X-Z PLANES

TABLE 24

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 5TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From SRP-V

Horizontal Plane	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
	Vector — Degrees From Forward*																							
+137 cm																								
(54 in)																								
+122 cm																								
(48 in)																								
+107 cm	14	12	11	10	10	10	10	11	13	15	18	23	25	28	31	33	35	36	36	33	27	22	20	16
(42 in)																								
+ 91 cm	23	21	20	19	18	20	21	23	28	34	39	42	46	48	51	53	54	57	56	42	33	29	25	27
(36 in)	10	10	9	9	8	8	8	9	10	10	11	11	11	10	10	9	8	8	8	9	9	10	10	10
+ 76 cm	17	17	18	20	20	10	25	33	41	44	49	51	55	58	61	63	65	65	66	33	31	25	23	23
(30 in)	6	6	6	7	7	6	6	7	8	10	11	13	11	10	8	7	6	6	7	7	6	6	6	6
+ 61 cm							31	36	44	50	53	57	61	64	57	69	70	71	72					
(24 in)							24	20	16	14	12	11	12	14	16	20	29	41	48					
+46 cm						26	29	34	43	50	53	57	62	65	67	69	71	72	71					
(18 in)						18	18	18	17	17	17	17	17	17	17	18	34	39	60					
+ 30 cm							27	32	38	43	48	40	60	62	65	67	69	70	67					
(12 in)							18	18	20	21	20	20	20	21	20	22	28	32	41					
+ 15 cm														56	57	60	61	61	59	58	55			
(6 in)														43	30	24	19	15	23	37	36			
0 cm															41	41	43	43	40	39	30			
(SRP)																								
− 15 cm																								
(−6 in)																								

*Axis is SRP-V

TABLE 25

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 50TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From SRP-V

Horizontal Plane	Vector — Degrees From Forward*																						
	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R50	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm																								
(54 in)																								
+122 cm	18	17	16	15	14	14	14	15	16	18	20	22	25	27	30	33	35	37	37	37	30	24	22	20
(48 in)																								
+107 cm	32	29	27	24	25	27	30	32	38	42	44	46	50	54	57	60	62	64	64	60	52	42	39	37
+ 91 cm	36	30	27	28	29	33	38	43	47	52	56	60	63	67	59	73	72	74	74	69	51	44	44	39
(36 in)	10	10	9	9	8	8	8	9	10	10	11	11	11	10	10	9	8	8	8	9	9	10	10	10
+ 76 cm	30	28	27	29	33	37	45	49	53	58	62	67	70	74	76	79	79	80	80	74	46	41	39	35
(30 in)	6	6	6	7	7	6	6	7	8	10	11	13	11	10	8	7	6	6	7	7	6	6	6	6
+ 61 cm	22	20	23	27	35	40	46	51	57	61	65	69	74	76	79	82	81	84	82	77	33	29	27	25
(24 in)	10	11	15	19	24	27	24	20	16	14	12	11	12	14	16	20	24	27	24	19	15	11	10	11
+ 46 cm					30	37	43	50	55	60	64	68	72	75	79	81	81	82	81	77				
(18 in)					18	18	18	18	17	17	17	17	17	17	17	18	19	23	27	44				
+ 30 cm						34	39	43	50	53	58	64	68	71	74	76	76	77	76	74	67	51		
(12 in)												60												
						17	18	20	20	21	20	40	20	21	20	20	18	17	23	31	42	35		
												20												
+ 15 cm													60	64	65	67	68	69	67	65	61	53	43	
(6 in)													60	43	30	24	19	15			28	32	36	
0 cm														46	51	51	53	53	53	49	44	37	27	
(SRP)																								
− 15 cm																		23						
(−6 in)																								

*Axis is SRP-V

TABLE 26

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 95TH PERCENTILE
HORIZONTAL PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From SRP-V

Vector — Degrees From Forward*

Horizontal Plane	L165	L150	L135	L120	L105	L90	L75	L60	L45	L30	L15	Fwd 0	R15	R30	R45	R60	R75	R90	R105	R120	R135	R150	R165	Aft 180
+137 cm (54 in)	21	20	20	18	18	18	18	19	20	22	23	25	28	30	34	37	40	41	38	35	30	26	23	22
+122 cm (48 in)	43	40	37	34	32	33	36	40	44	48	51	53	56	60	63	65	65	66	66	64	60	57	52	48
+107 cm (42 in)	50	47	46	43	41	41	44	51	56	61	64	69	71	75	77	79	79	79	79	79	71	66	63	55
+ 91 cm	51	50	50	48	46	47	51	59	64	67	72	76	79	83	85	86	88	87	87	87	79	67	62	57
(36 in)	10	10	9	9	8	8	8	9	10	10	11	11	11	10	10	9	8	8	8	9	9	10	10	10
+ 76 cm	52	50	41	45	47	53	58	64	69	72	77	81	85	88	89	91	92	91	91	90	84	60	57	54
(30 in)	6	6	6	7	7	6	6	7	8	10	11	13	11	10	8	7	6	6	7	7	6	6	6	6
+ 61 cm	38	37	36	43	48	56	59	64	69	74	79	83	87	89	91	93	93	93	93	91	86	56	43	41
(24 in)	10	11	15	19	24	27	24	20	16	14	12	11	12	14	16	20	24	27	24	19	15	11	10	11
+ 46 cm				34	42	51	56	60	66	72	76	81	86	88	90	90	92	91	91	88	86	71	38	
(18 in)					18	18	18	18	17	17	17	17	17	17	17	18	18	18	18				27	
+ 30 cm				29	36	44	50	56	61	65	71	77	82	84	84	85	88	87	86	83	81	75	64	
(12 in)												60												
					15	17	18	20	20	21	20	40	20	21	20	20	18	17	15				34	
												20												
+ 15 cm					26	34	41	48	53	57	65		75	77	79	79	79	81	79	76	73	68	60	47
(6 in)						15	19	24	30	43	60		60	43	30	24	19	15	23	18	21	28	31	32
0 cm (SRP)													60	64	65	67	67	67	65	64	58	51	46	36
− 15 cm (−6 in)														46	47	47	46	44	44	44	41			

*Axis is SRP-V

TABLE 27

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 5TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes*																					
	−61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)																						
+122 cm (48 in)																						
+107 cm (42 in)							1	29	10	36												
+ 91 cm (36 in)							13	55	8	57	20	52	17	43								
									20	8												
+ 76 cm (30 in)							5	64	6	65	28	63	28	55	15	39						
									23	6												
+ 61 cm (24 in)								71		71	31	69	31	62	21	49						
								47		41												
+ 46 cm (18 in)								70	18	72	8	70	30	64	22	51						
								58	26	39	29	8										
+ 30 cm (12 in)								66		70	13	67	25	60	11	46						
								42		32	27	13			13	11						
+ 15 cm (6 in)						50		57		61		60		51		34						
						23		33		22		22		22		10						
0 cm (SRP)								37		43		40										
								18		22		22										
− 15 cm (−6 in)																						

* +=Forward, −=Aft from SRP-V

TABLE 28

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 50TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Frontal Planes*

Horizontal Plane	−61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)																						
+122 cm (48 in)							8	19	14	37	9	30										
+107 cm (42 in)					9	51	20	62	27	64	25	60	25	52	4	30						
+ 91 cm (36 in)					13	65	23	72	8	74	37	71	35	66	27	55		23				
							33	8														
+ 76 cm (30 in)					6	72	24	79	6	80	44	78	41	73	34	63	15	42				
								37	6													
+ 61 cm (24 in)						75		82	27	84	46	81	44	75	37	68	20	48				
						41		22	40	27												
+ 46 cm (18 in)						74		80	18	82	8	80	42	75	35	66	18	46				
						41		32	37	23	43	8										
+ 30 cm (12 in)				53		69		76	17	77	13	75	36	70	11	60	6	37				
				30		18		27	34	17	38	13			28	11						
+ 15 cm (6 in)				33		58		66		69		67		60		47						
				25		15		20		22		22		22		3						
0 cm (SRP)						34		50		53		50		41								
						16		15		22		22		22								
− 15 cm (+6 in)										23												
										15												

* +=Forward, −=Aft from SRP-V

TABLE 29

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 95TH PERCENTILE
VERTICAL Y-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From Fore-Aft Plane
Through SRP-V

Horizontal Plane	Frontal Planes*																					
	−61 cm (24 in)		−46 cm (18 in)		−30 cm (12 in)		−15 cm (6 in)		0 cm (0 in)		+15 cm (6 in)		+30 cm (12 in)		+46 cm (18 in)		+61 cm (24 in)		+76 cm (30 in)		+91 cm (36 in)	
	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT	LT	RT
+137 cm (54 in)							12	32	18	41	14	36										
+122 cm (48 in)			3	37	23	56	30	64	33	66	34	64	31	58	19	43						
+107 cm (42 in)		19 17	17	60	34	74	39	78	41	79	44	77	43	73	37	64	19	46				
+ 91 cm (36 in)			20	74	38	83	44	86	8 47	87 8	51	86	51	82	45	74	32	60	2	20		
+ 76 cm (30 in)			22	78	29	86	44	90	6 53	91 6	57	91	56	87	50	79	38	65	15	42		
+ 61 cm (24 in)		62 44		79 23	22	88	22 44	92 22	27 56	93 27	57	92	55	89	50	81	41	69	20	46		
+ 46 cm (18 in)		62 35		76 17		86 7	25 33	91 15	18 51	91 18	8 54	91 8	52	87	48	77	39	66	15	43		
+ 30 cm (12 in)		51 15		69 8		79 10	23 25	86 15	17 44	87 17	13 48	86 15	48	81	11 41	72 11	29	58	3	35		
+ 15 cm (6 in)			1	60		71 5		78 15	22 34	81 22	22 41	78 22	22 41	72 22	2 20 32	64	15 19	50 11				
0 cm (SRP)					3	57		64 15		67 22		65 22		60 22		46 15						
− 15 cm (−6 in)								41 15		44 15		43 15		36 15								

* +=Forward, −=Aft from SRP-V

TABLE 30

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 5TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From Frontal Plane
Through SRP-V

Horizontal Plane	Fore/Aft Planes* +61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		+76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)																						
+107 cm (42 in)									23	16	24	19	15	15								
+ 91 cm (36 in)							33	13	42 11	10 27	44	25	39	23	28	20						
+ 76 cm (30 in)							46	11	51 13	6 23	53	22	50	17	41	20	21	22				
+ 61 cm (24 in)					33 8		50 11		57 12		59 11		57 6		48	9	32	28				
+ 46 cm (18 in)							50 10		57 17		60 10		57 10		49	6	34	27				
+ 30 cm (12 in)							43 13		40 20		57 13		55 3		46	19	29	22				
+ 15 cm (6 in)													47	11 20 41	36	34	8	0				
0 cm (SRP)												10 10	23	22								
− 15 cm (−6 in)																						

* + =Left, − =Right from SRP-V

TABLE 31

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 50TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From Frontal Plane
Through SRP-V

Horizontal Plane	Fore/Aft Planes* +61 cm (24 in) Fore	Aft	+46 cm (18 in) Fore	Aft	+30 cm (12 in) Fore	Aft	+15 cm (6 in) Fore	Aft	0 cm (0 in) Fore	Aft	−15 cm (6 in) Fore	Aft	−30 cm (12 in) Fore	Aft	−46 cm (18 in) Fore	Aft	−61 cm (24 in) Fore	Aft	+76 cm (30 in) Fore	Aft	−91 cm (36 in) Fore	Aft
+137 cm (54 in)																						
+122 cm (48 in)									22	20	23	21	14	19								
+107 cm (42 in)							41	24	46	38	49	36	46	37	37	34	13	18				
+ 91 cm (36 in)					39	5	53	27	60 11	10 39	61	42	60	37	51	39	39	33				
+ 76 cm (30 in)					50	10	60	23	67 13	6 35	69	37	66	33	58	36	48	39	18	24		
+ 61 cm (24 in)			18 15		53	10	63 11		69 12	18 25	71 11	18 26	69	25	62	36	53	43	27	28		
+ 46 cm (18 in)					51	7	62 10		68 17		70 10		67	13	62	39	51	43	29	26		
+ 30 cm (12 in)					43	3	55 13		64 60 40 20		66 13		64	22 29 46	57	48	44	40	10	13		
+ 15 cm (6 in)											58 57	29 44	56	46	46	42	29	26				
0 cm (SRP)												20 30	38	32	23	22						
− 15 cm (−6in)																						

* +=Left, −=Right from SRP-V

TABLE 32

REACH CAPABILITY ENVELOPE
50/50 MEN AND WOMEN, 95TH PERCENTILE
VERTICAL X-Z PLANES

Back Angle 13 Degrees Aft of Vertical
Seat Angle 6 Degrees Above Horizontal

N=60
Values in Centimeters
From Frontal Plane
Through SRP-V

Fore/Aft Planes*

Horizontal Plane	+61 cm (24 in)		+46 cm (18 in)		+30 cm (12 in)		+15 cm (6 in)		0 cm (0 in)		−15 cm (6 in)		−30 cm (12 in)		−46 cm (18 in)		−61 cm (24 in)		+76 cm (30 in)		−91 cm (36 in)	
	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft	Fore	Aft
+137 cm (54 in)							12	11	25	22	27	23	21	17								
+122 cm (48 in)					32	15	48	39	53	48	54	50	52	49	43	40	23	23				
+107 cm (42 in)					53	35	63	46	69	55	69	62	67	58	61	53	48	44	20	25		
+ 91 cm (36 in)			45	7	62	39	72	49	76 11	10 57	77	60	75	59	71	58	60	54	41	43		
+ 76 cm (30 in)			53	12	68	29	76	50	81 13	6 54	83	55	81	52	74	57	65	59	51	48	3	3
+ 61 cm (24 in)			53	14	71	24	79 11	18 35	83 12	18 41	84 11	18 43	83	50	76	62	67	62	53	50	20	18
+ 46 cm (18 in)			48	8	67	17	76 10		81 17		83 10	13 44	81	59	75	64	66	62	48	45	5	3
+ 30 cm (12 in)			36 3		60	13	70 13		77 60 40 20		79 13	11 61	77	65	71	64	59	55	39	36		
+ 15 cm (6 in)					47	3	65 57			32 47	72 57	10 58	70	60	64	55	50	44	20	20		
0 cm (SRP)										20 36	58 39	10 44	56	44	46	39	27	22				
− 15 cm (−6 in)											43	20	36	29								

* +=Left, −=Right from SRP-V

APPENDIX III

ANTHROPOMETRIC DATA AND DESCRIPTIONS

DESCRIPTIONS OF ANTHROPOMETRIC DIMENSIONS*

HEIGHT: Subject stands erect looking directly forward (head oriented in the Frankfort Plane). With the anthropometer arm firmly touching the scalp, measure the vertical distance from the floor to the top of the head.

FUNCTIONAL REACH: Subject stands erect in a corner of the room, his shoulders pressed against the rear wall, except that the tips of his thumb and forefinger are pressed together. Using the scale on the side wall, measure the distance from the rear wall to the tip of the thumb.

SITTING HEIGHT: Subject sits erect, looking directly forward (head oriented in the Frankfort Plane), and his feet resting on a surface so that his knees are bent at about right angles. With the anthropometer arm firmly touching the scalp, measure vertically from the sitting surface to the top of the head.

EYE HEIGHT, SITTING: Subject sits erect, looking directly forward (head oriented in the Frankfort Plane), and his feet resting on a surface so that his knees are bent at about right angles. With the anthropometer, measure vertically from the sitting surface to the pupil of the right eye.

ACROMION HEIGHT, SITTING: Subject sits erect, his feet resting on a surface so that the knees are bent at about right angles. Using the anthropometer, measure the vertical distance from the sitting surface to right acromion as marked.

BUTTOCK-KNEE LENGTH: Subject sits erect, his feet resting on a surface so that the knees are bent at about right angles. Using the anthropometer, measure the horizontal distance from the rearmost point of the right buttock to the front of the kneecap.

BIACROMIAL DIAMETER: Subject sits erect, his upper arms hanging at his sides and his forearms extended horizontally. Using the anthropometer, measure between the points marked at the ends of the shoulders (acromion to acromion).

SHOULDER BREADTH: Subject sits erect, his upper arms hanging at his sides, and his forearms extended horizontally. Using the anthropometer, measure the horizontal distance across the maximum lateral protrusion of the deltoid muscles.

SHOULDER-ELBOW LENGTH: Subject sits erect, his right upper arm hanging at his side and his forearm extended horizontally. Using the anthropometer, measure the vertical distance from right acromion as marked to the bottom of the elbow.

FOREARM-HAND LENGTH: Subject sits erect, his right upper arm hanging at his side, his forearm and hand extended horizontally. Using the anthropometer, measure the distance from the tip of the right elbow to the tip of the longest finger.

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*All descriptions except Eye Height, Sitting, are from Hertzberg, Daniels, and Churchill (1954).

TABLE 33

ANTHROPOMETRIC MEANS AND STANDARD DEVIATIONS
COMPARATIVE DATA — WOMEN

Dimension	Study Sample* N = 30		Health Exam** N = 6671		US Air Force*** N = 1905	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Age	20.8	4.03	42.6	15.4	23.4	6.45
Height	162.9	5.74	160.3	6.58	162.1	6.00
Weight	56.5	5.57	63.7	13.8	57.7	7.52
Functional Reach	71.9	3.53			74.1	3.88
Sitting Height	86.3	2.65	81.8	3.83	85.6	3.17
Eye Height, Sitting	73.6	2.63			73.7	3.06
Acromion Height, Sitting	55.5	2.53				
Buttock-Knee Length	57.5	2.16	56.8		57.4	2.63
Biacromial Diameter	36.2	1.54	35.4	1.93	35.8	1.64
Shoulder Breadth	41.8	1.99			41.9	2.31
Shoulder-Elbow Length	32.5	1.67			33.3	1.87****
Forearm-Hand Length	42.5	1.98				

Age is reported in years; Weight in Kilograms; Others in Centimeters

*The subject population consisted of college students from the University of Dayton, Dayton, Ohio, and research personnel at the Aerospace Medical Research Laboratory. All were caucasian. An attempt was made to approximate, in terms of body segment lengths, the Women's Air Force (WAF) and USAF nurses.

**Stoudt, McFarland and Roberts (1965)

***Clauser, et al. (1968)

****Randall and Baer (1951)

TABLE 34

ANTHROPOMETRIC MEANS AND STANDARD DEVIATIONS
COMPARATIVE DATA — MEN

Dimension	Study Sample* N = 30		Health Exam** N = 6666		US Air Force*** N = 2420	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Age	26.7	7.42	43.2	15.5	30.0	6.31
Height	179.6	5.55	173.3	6.88	177.3	6.19
Weight	80.0	7.74	74.9	12.6	78.7	9.72
Functional Reach	80.9	3.50			80.3	3.98
Sitting Height	93.5	3.39	86.4	3.68	93.2	3.18
Eye Height, Sitting	78.7	4.21			80.9	3.02
Acromion Height, Sitting	61.4	4.07			61.1	2.85
Buttock-Knee Length	62.8	4.44	59.1	9.92	60.4	2.70
Biacromial Diameter	41.2	1.83	39.6	2.11	40.7	1.94
Shoulder Breadth	48.9	2.01			48.2	2.56
Shoulder-Elbow Length	37.0	1.35			35.9	1.71
Forearm-Hand Length	48.6	1.76			47.9	2.03****

Age is reported in years; Weight in Kilograms; Others in Centimeters

*The subject population consisted of college students from the University of Dayton, Dayton, Ohio, and research personnel at the Aerospace Medical Research Laboratory. All were caucasian. An attempt was made to approximate, in terms of body segment lengths, the US Air Force flying officers (male).

**Stoudt, McFarland, and Roberts (1965)

***Grunhofer and Kroh (1975)

****Hertzberg, Daniels, and Churchill (1954)

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